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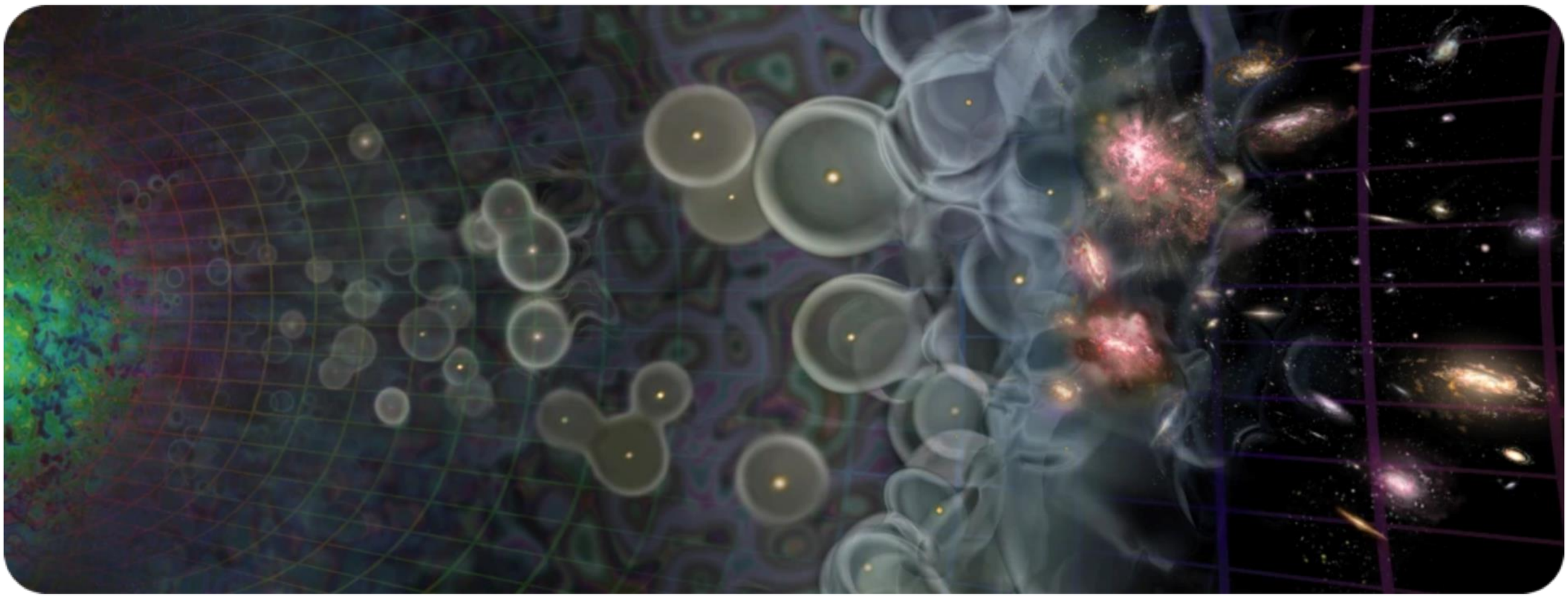
Observing the Epoch of Reionisation and Cosmic Dawn with LOFAR and NenuFAR

Léon Koopmans, (Kapteyn Astronomical Institute, University of Groningen, NL)

A presentation also on behalf of the LOFAR, NenuFAR, AARTFAAC, NCLE, ALO teams



European Research Council
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LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

Supported in part by
an ERC Advanced Grant “CoDEX”

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What can “21-cm Cosmology” tell us?

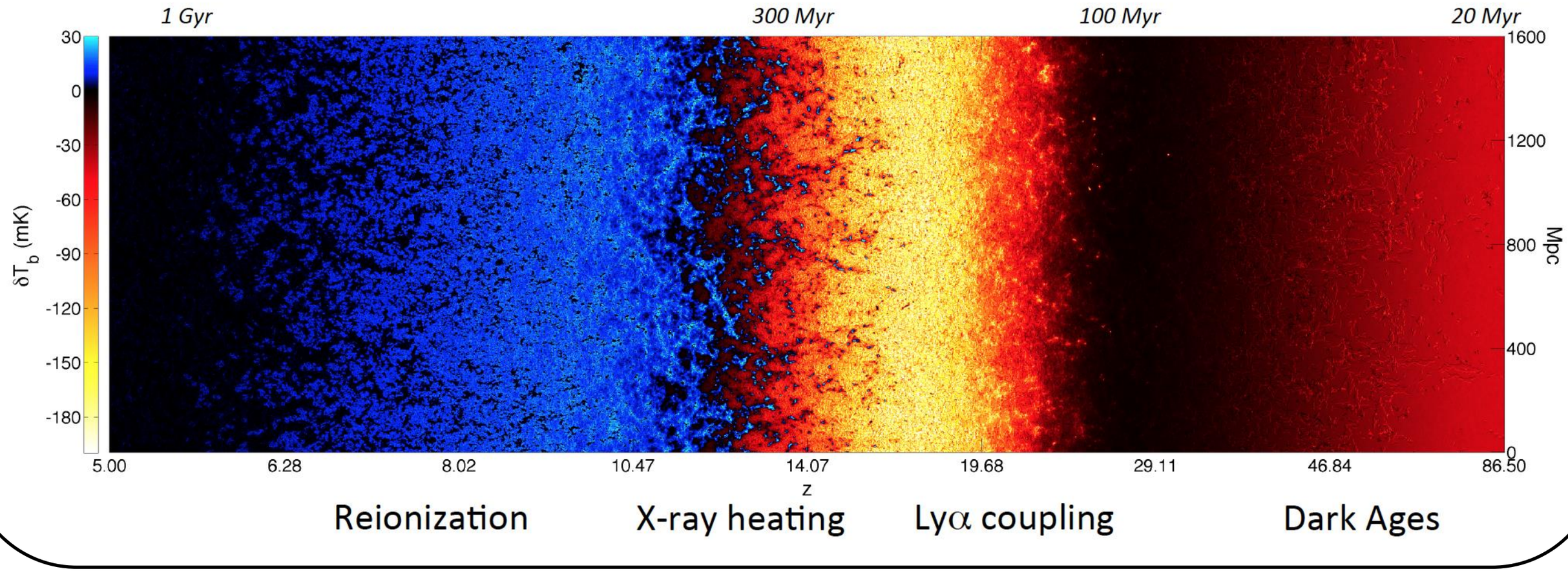
LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

What can “21-cm Cosmology” tell us?

The tomography of HI emission/absorption is a treasure trove of information for (astro)physics, cosmology & fundamental physics.

Post-Reionization | Reionization | Cosmic Daw | Dark Ages

HI is found largely in galaxies ← HI has a filling factor of order unity



Credit figure: Mesinger

What can “21-cm Cosmology” tell us?

The brightness of the 21-cm signal (in Kelvin; Rayleigh-Jeans regime) that can be measured with radio telescopes is given by:

$$\delta T_b = \frac{T_S - T_R}{1+z}\left(1 - \mathrm{e}^{-\tau_\nu}\right)$$

$$\approx \frac{T_S - T_R}{1+z}\tau$$

Cosmology

$$\approx 27 x_{\rm HI}\,(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2}$$

$$\times\left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]\ \mathrm{mK},$$

Ionization

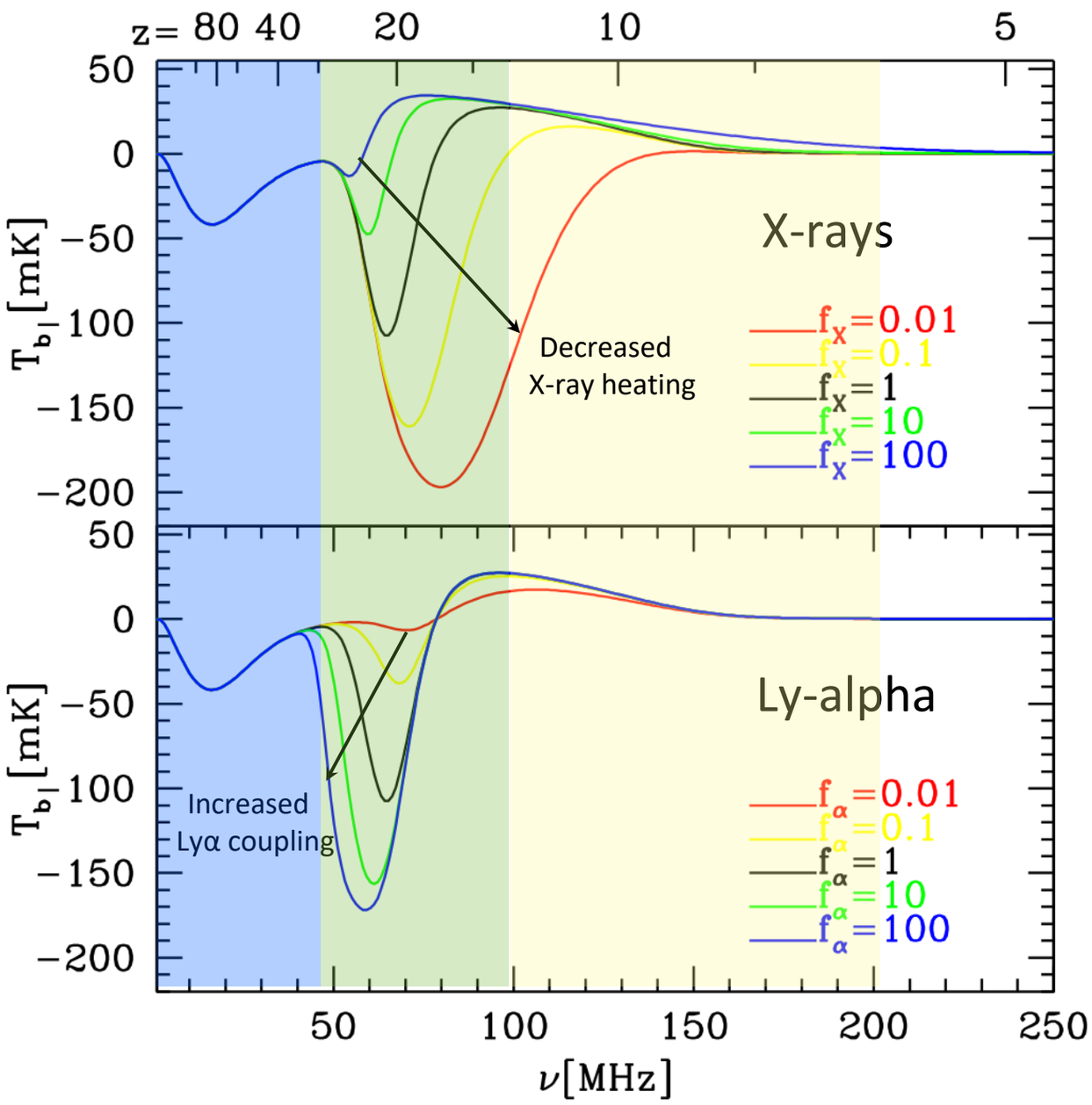
(G)astrophysics

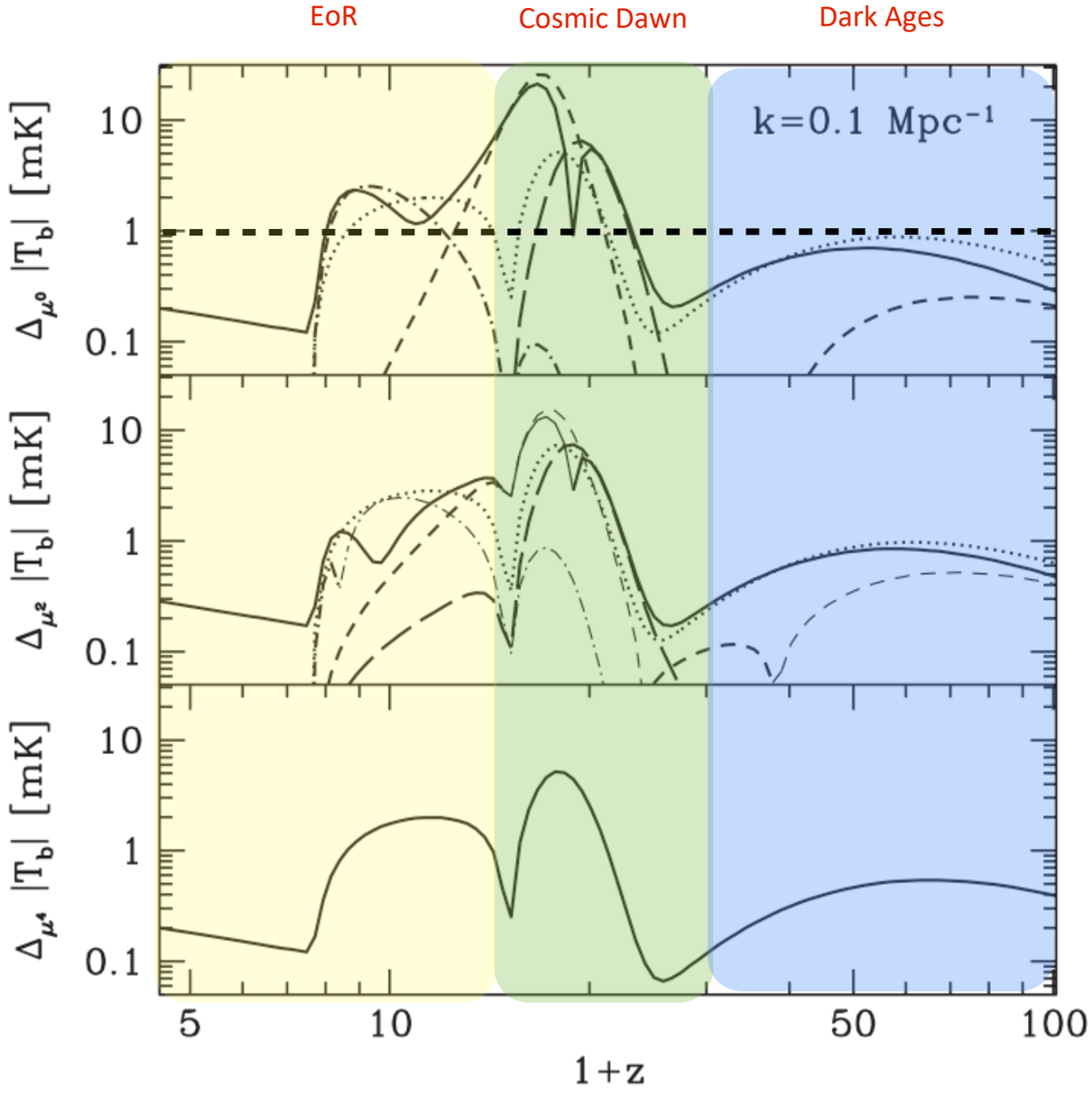
Peculiar velocities/Bulk-flows

The 21-cm signal is set by a complex interplay between cosmology and (g)astrophysics.

What can “21-cm Cosmology” tell us?

Global Signal (left) and Intensity Fluctuations (right)

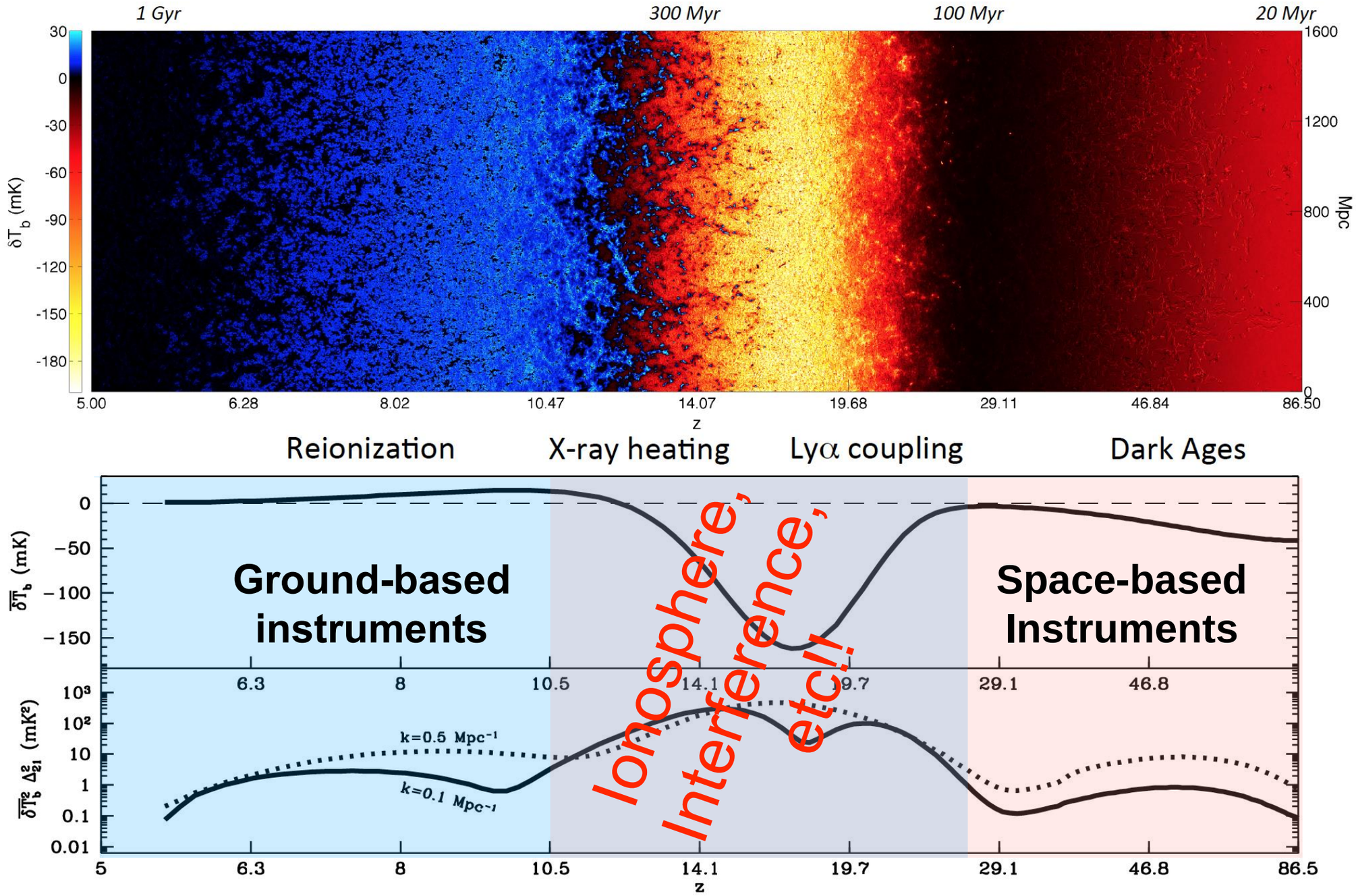




Pritchard & Loeb 2009; see also Santos et al. 2008, 2010, 2011

What can “21-cm Cosmology” tell us?

Between z~200* and z~6**, neutral hydrogen is a key tracer of fundamental physical processes (early stages) and unique astrophysical processes (later stages)

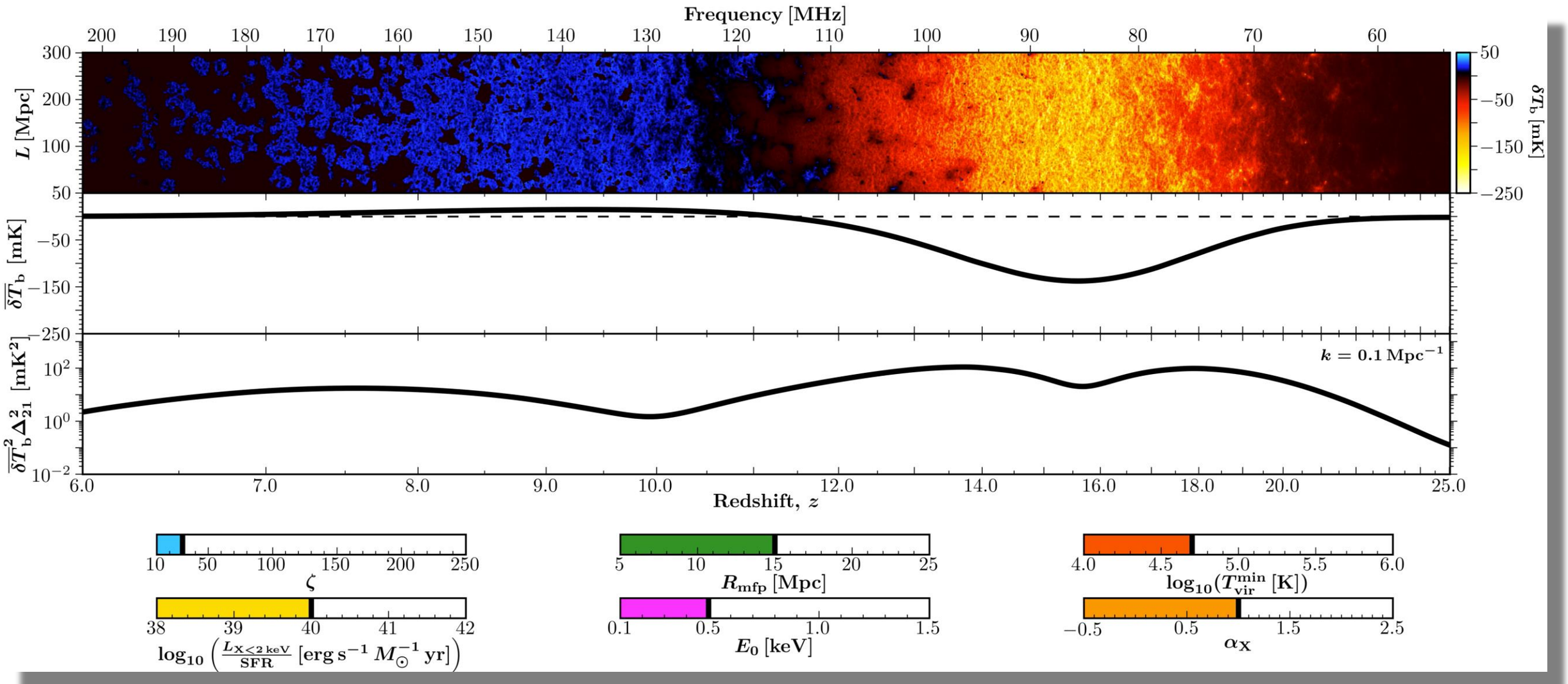


* Spin & CMB-temperature decouple; ** universe is reionized

What can “21-cm Cosmology” tell us?

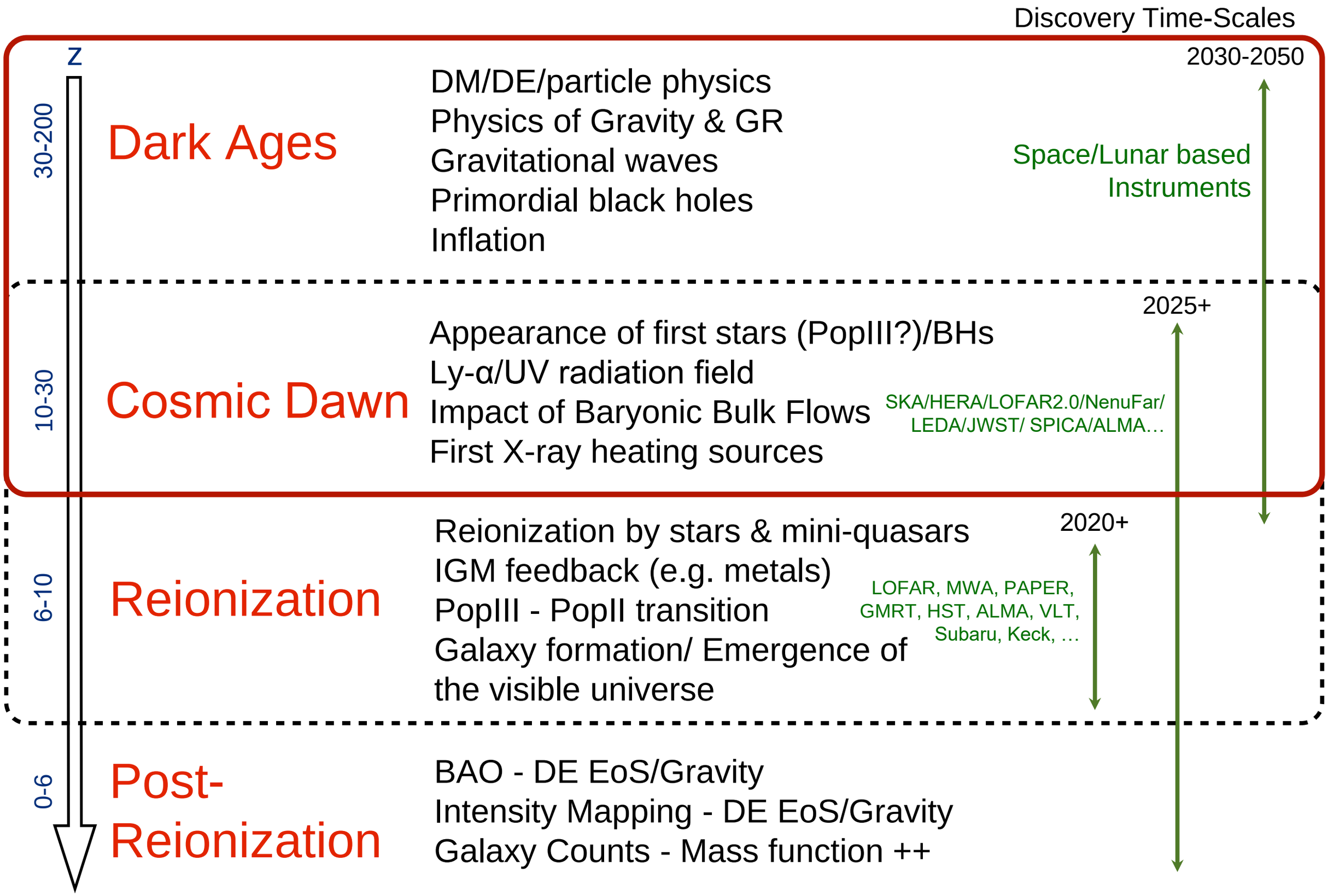
Numerical Models

Many “ingredients” in the 21-signal models are effective descriptions of the underlying complex physical processes (sub-grid physics) that we hope to connect to these processes on smaller (galaxy/stellar) scales.



Credit movie: Mesinger & Greig

What can “21-cm Cosmology” tell us?



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CoDEX Program:

A *broad-brush overview* of our 21-cm Cosmology programs with LOFAR[1], AARTFAAC, NenuFAR[2] and from space

1 See talks by Kariuki Chege & Stefanie Brackenhoff
2 See the talk by Satyapan Munshi

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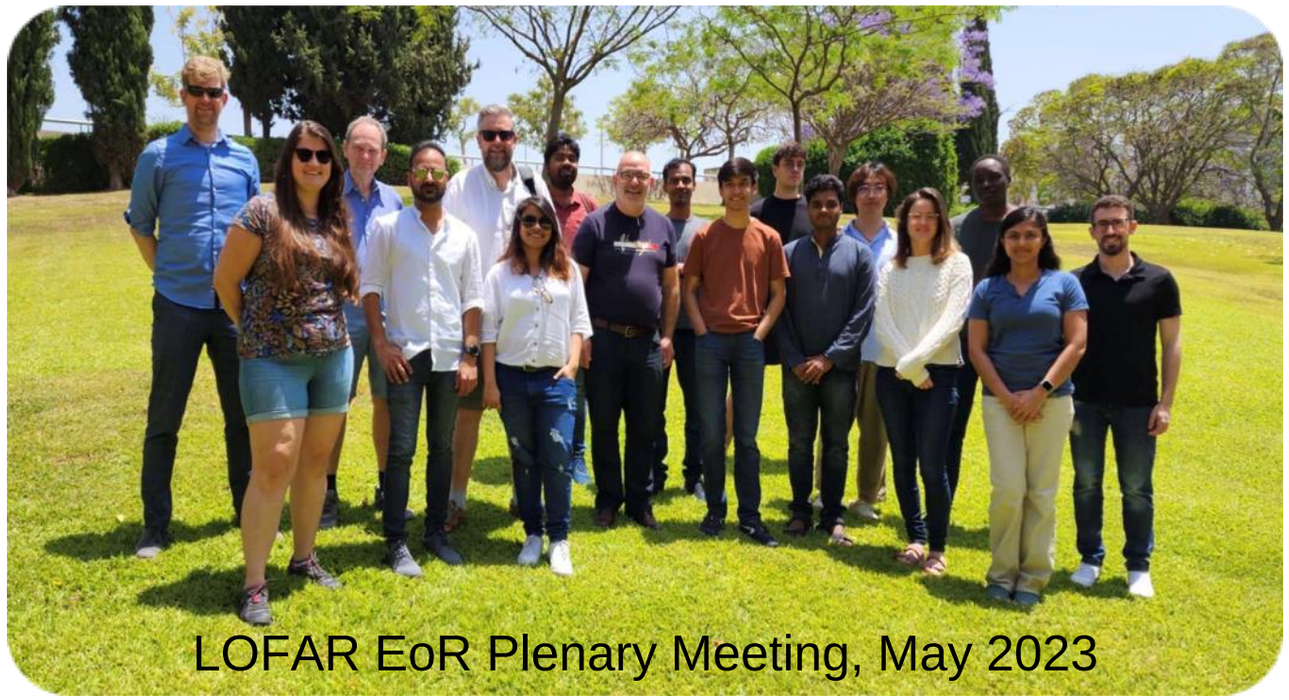
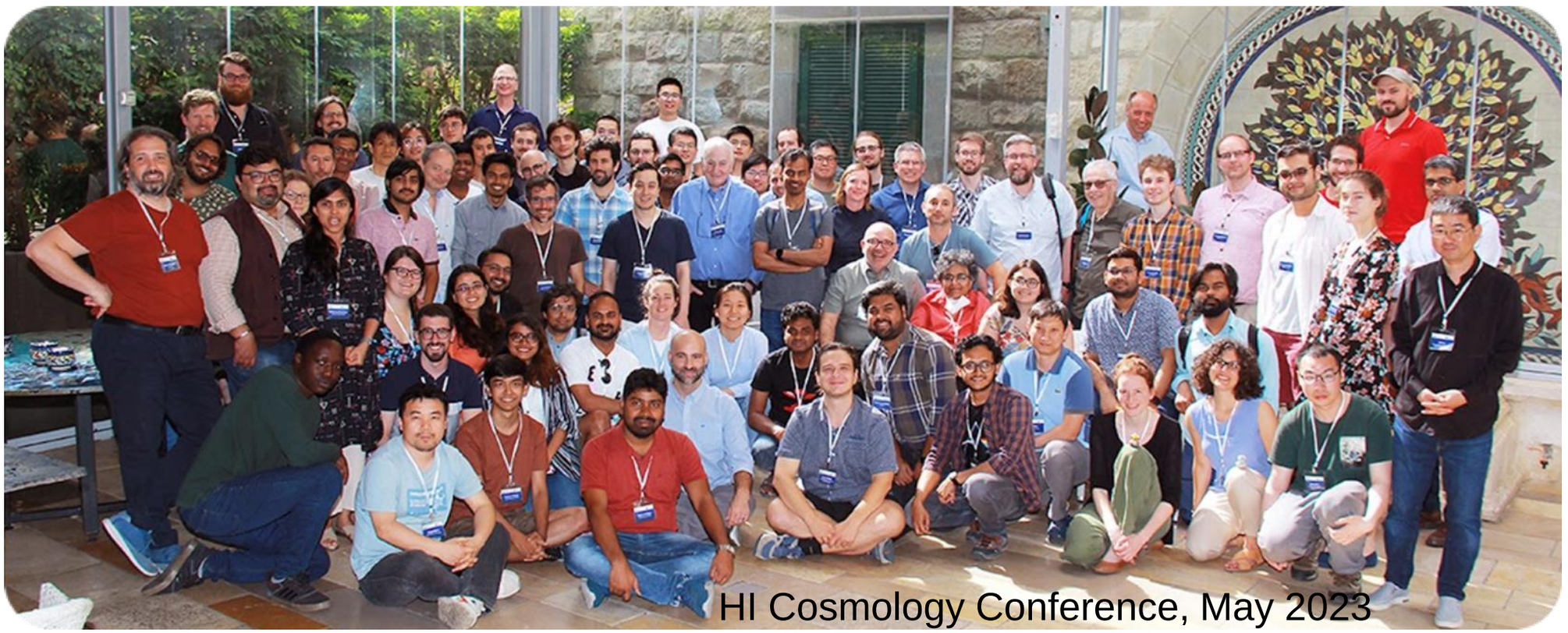
LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

The Team ++



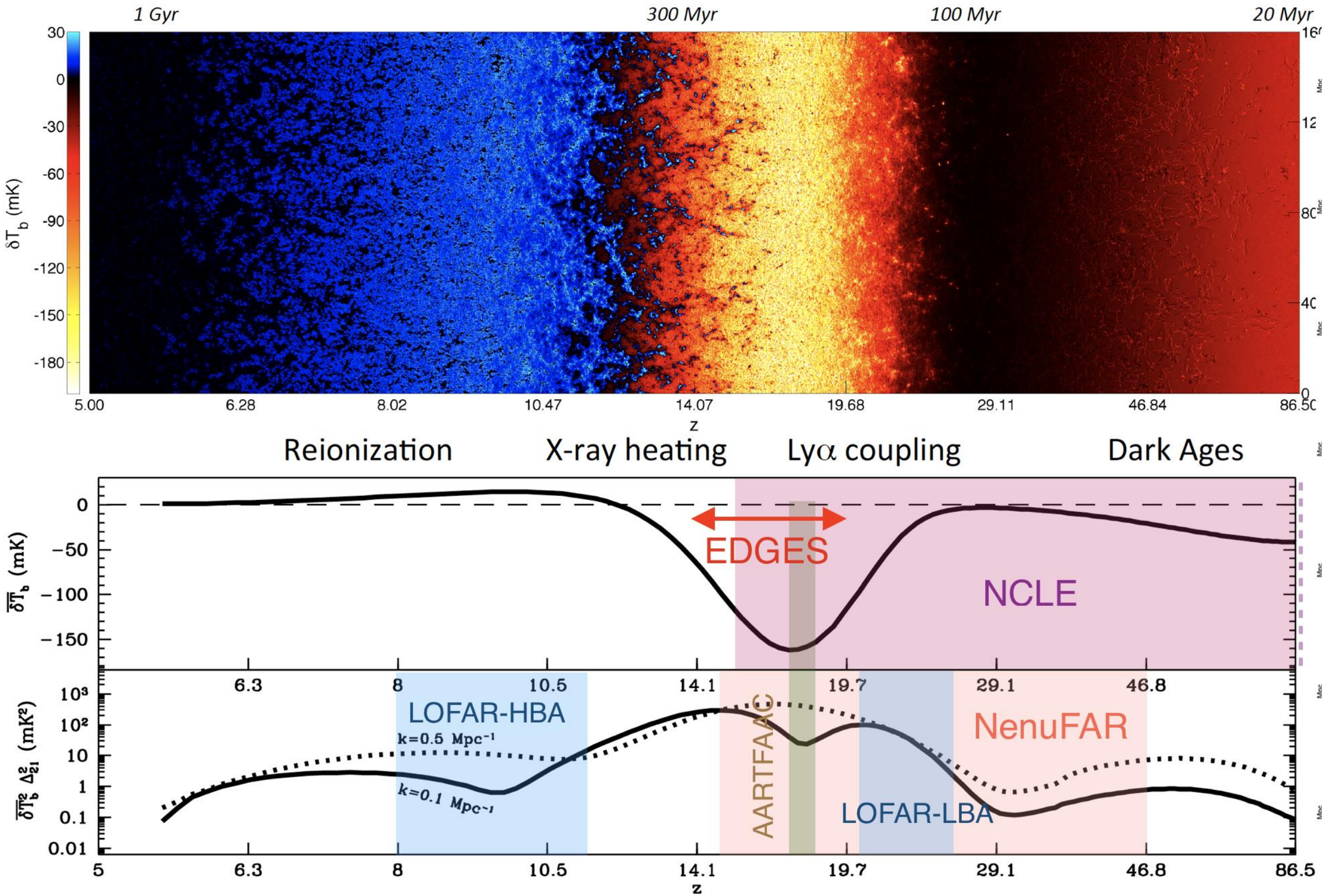
LOFAR EoR Plenary Meeting, May 2023

NenuFAR CD Plenary Meeting, May 2023



HI Cosmology Conference, May 2023

CoDEX — ERC-Advanced Program



CoDEX — ERC-Advanced Program

LOFAR EoR KSP

Power-spectra

3500h

z~6-11 — Epoch of Reionization

AARTFAAC Cosmic Explorer

Power-spectra

500h

z~18 — EDGES CD signal

NenuFAR CD KSP

Power-spectra

500h

z~12-30 — Cosmic Dawn

Netherlands China Low-frequency Explorer

Global Signal

Commissioning

z~12-200 — CD & Dark Ages

Astrophysical Lunar Observatory

Global Signal/ Power-spectra/ Tomography

z~12-50 — CD & Dark Ages

SKA CD/EoR KSP

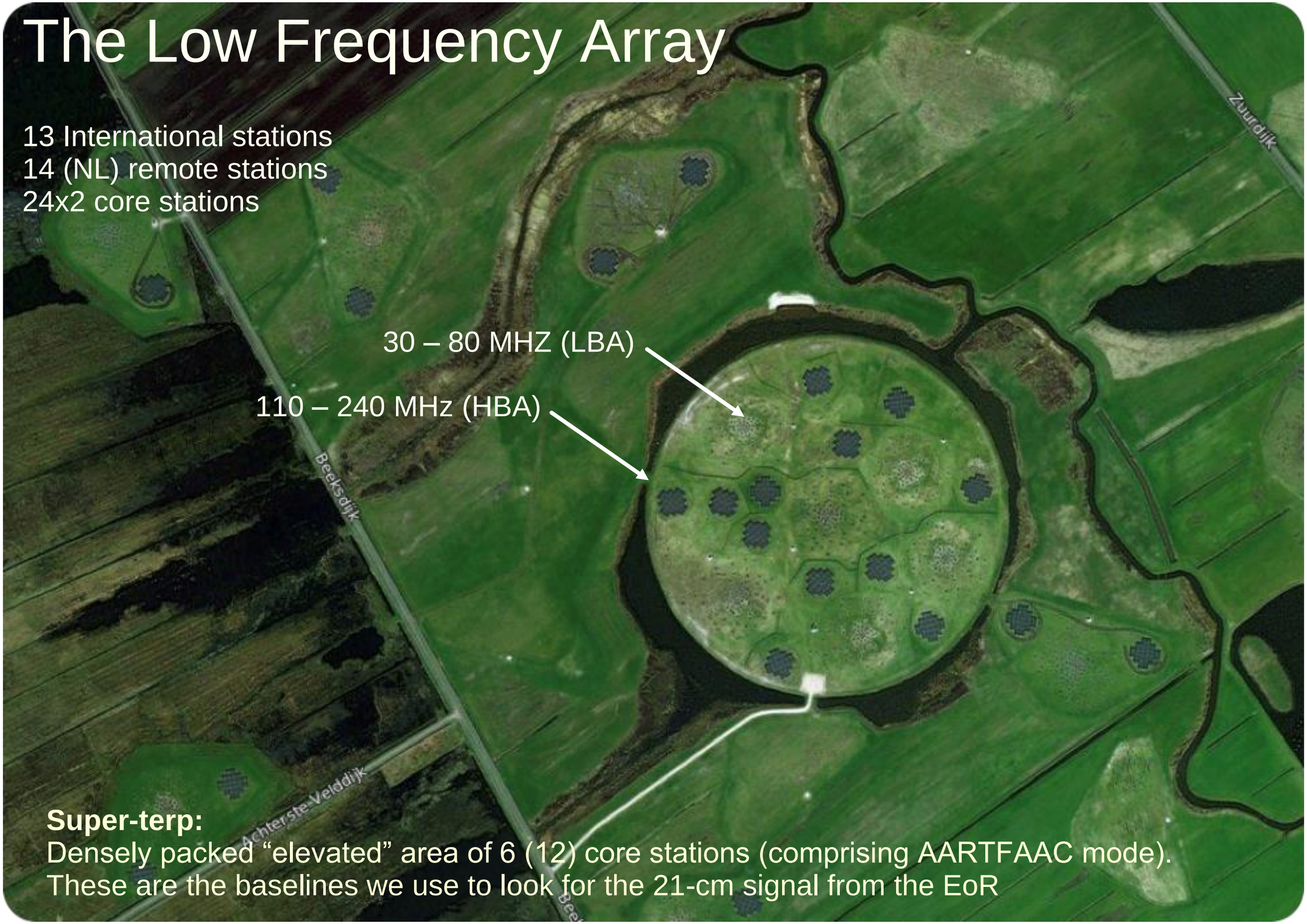
Power-spectra/ Tomography

z~3-27 — EoR & CD

European Research Council
Established by the European Commission

The Low Frequency Array

13 International stations
14 (NL) remote stations
24x2 core stations

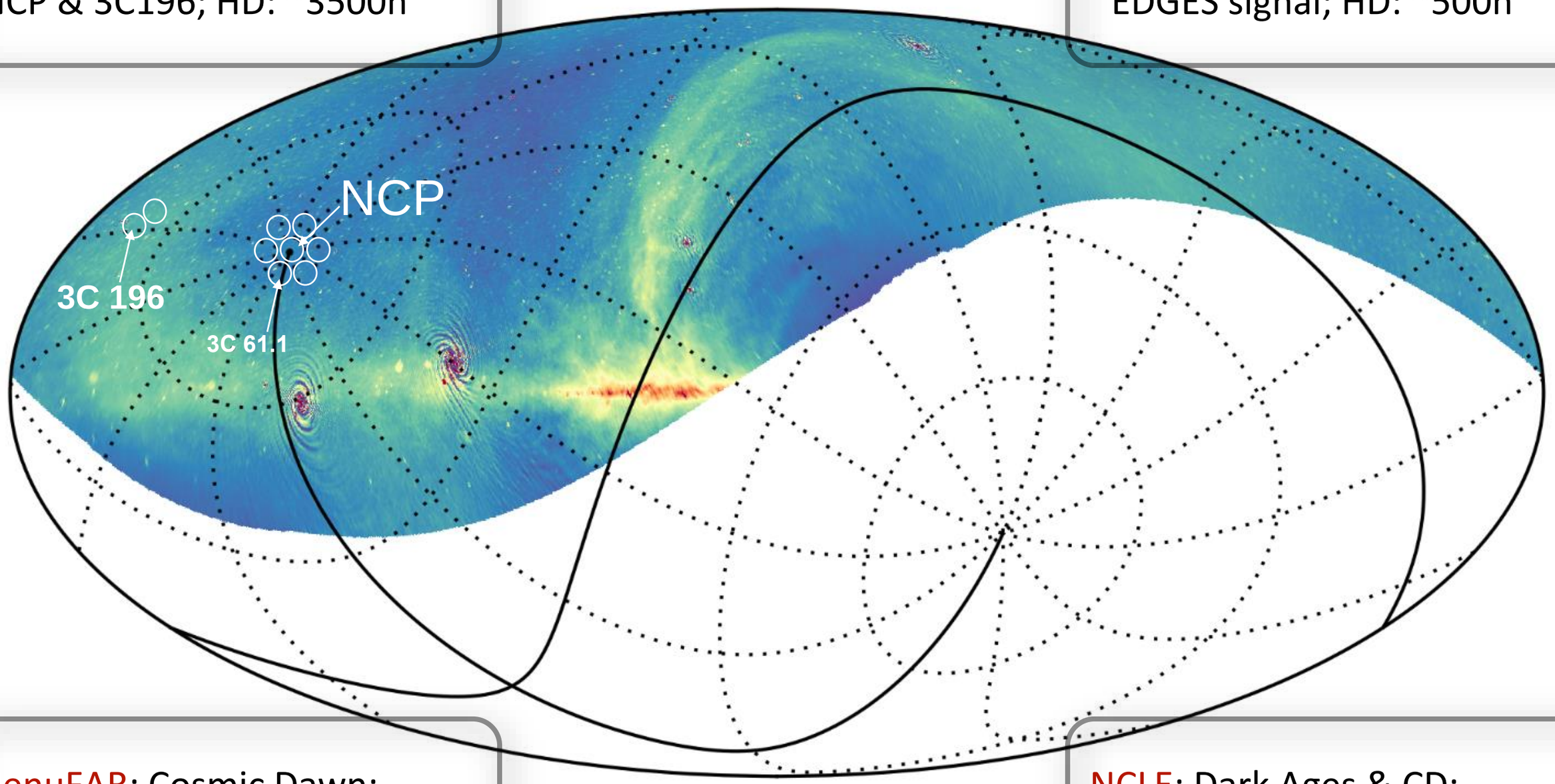


Super-terp:
Densely packed “elevated” area of 6 (12) core stations (comprising AARTFAAC mode).
These are the baselines we use to look for the 21-cm signal from the EoR

The Observational Windows

LOFAR: Epoch of Reionization;
NCP & 3C196; HD: ~3500h

AARTFAAC: Cosmic Dawn
EDGES signal; HD: ~500h



NenuFAR: Cosmic Dawn;
NCP; pilot/KSP: 400/1500+h

NCLE: Dark Ages & CD;
all-sky; commissioning, ~years

Image: AARTFAAC-LBA 70-73 MHz data (credit: Gehlot, Mertens)

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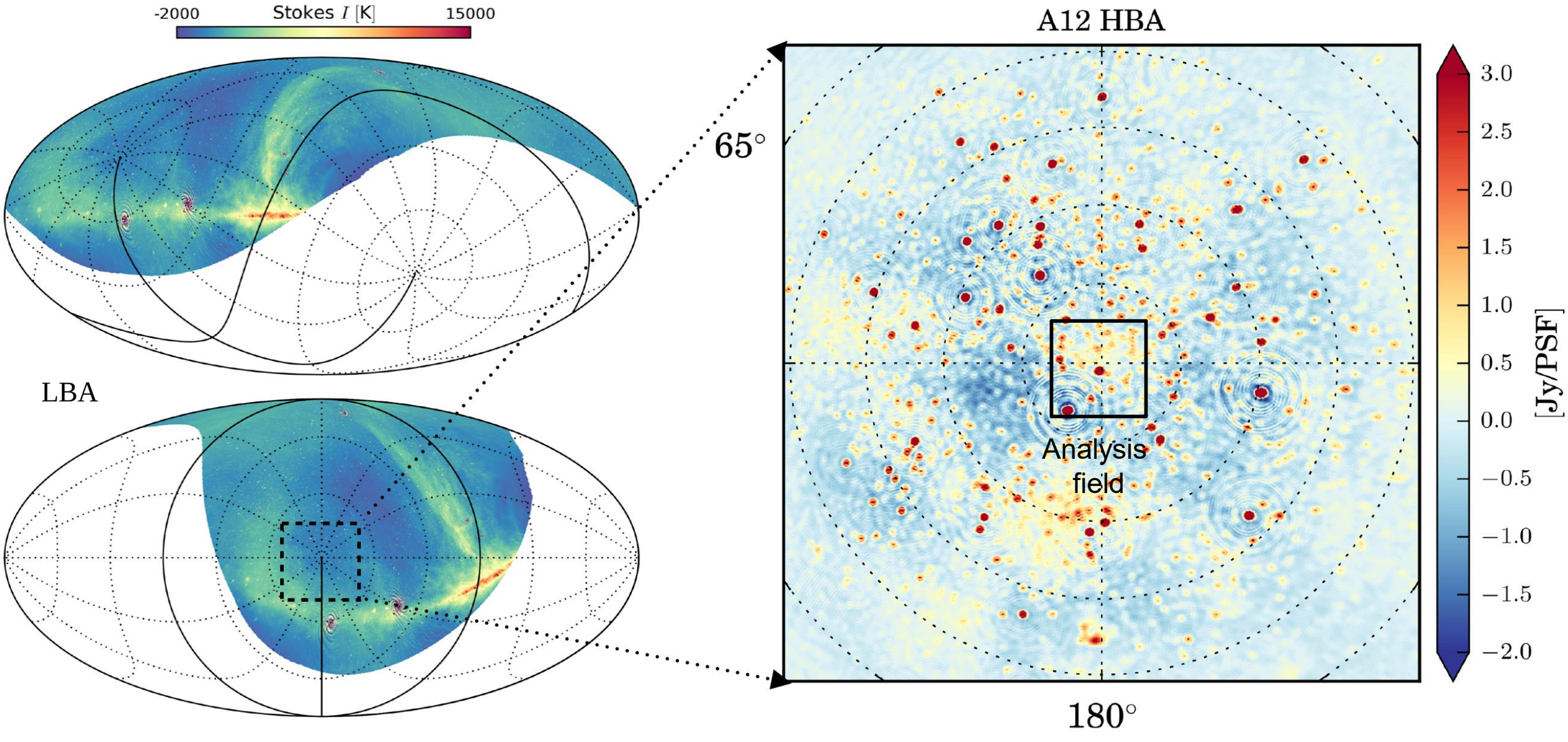
The Low Frequency Array
EoR Key Science Programme

LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

Primary EoR Window: North Celestial Pole

A complex field made of compact & extended (extra-galactic) sources and diffuse emission from the Galaxy (in Stokes I, Q, U, but hardly any Stokes V)



A recent wide-field view of the the NCP with LOFAR AARTFAAC-LBA- & HBA-12 system

Image credit: Bharat Gehlot & Florent Mertens

Peta-Byte/Flop Data Storage/Processing

Data processing of ~5+ petabytes of data in hand requires dedicated peta-flops processing capacity: “Dawn” & “CoDEX” GPU clusters

Part of “CoDEX” @ CIT-UG

CoDEX HPC – Main Specs

- CPU (AMD Milan) - 3040 CPU cores – 350 TFLOPS
- GPU (A100 PCIe 40GB, Nvidia) – 1.2 PFLOPS
- 4608 TByte HDD data storage
- 200 GbE network
- ~16 TB SSD (separate disk for boot/OS)
- Connection to Dawn 40Gb
- Connection to Surf 100Gb (proposed)
- 29 production nodes (256GB, 2 x A100 40GB, 2 x 48 core CPU)
- One High memory Innovation node (1TB, 2 x A100 80GB, 2 x 64 core CPUs)

The Data Analysis Pipeline

All data processing codes have been developed in house and open source
(many now in use by global community, e.g. AOFlagger, WSClean, etc) .

Processing pipeline

2019 – 2020

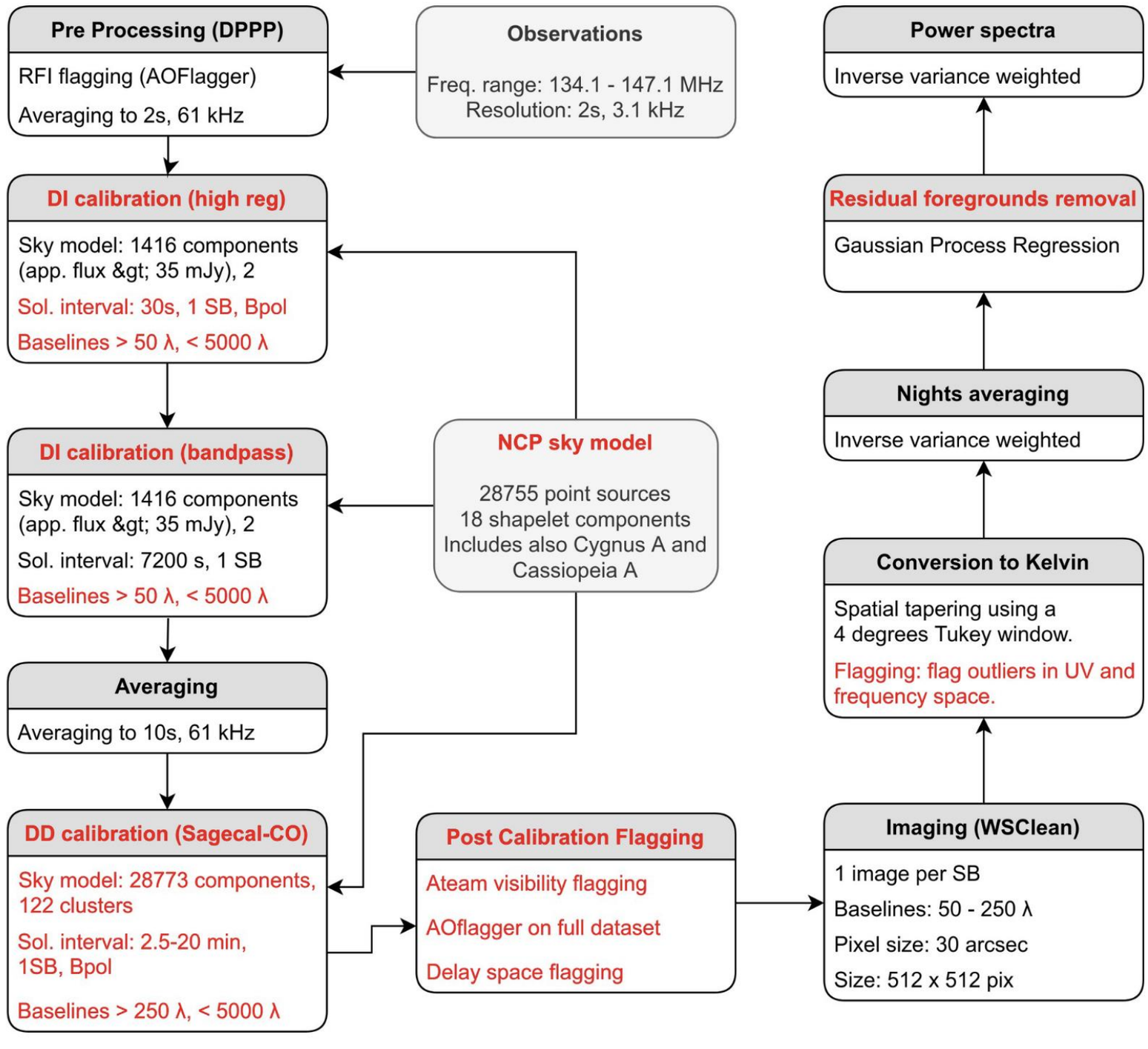
Improvements in DI calibration
- Separate Band-pass calibration
- Enforce smooth gain solutions

Improvements in RFI flagging
- Post calibration flagging
- Baseline flagging affected by local source of RFI

New improvements

Improvements in DD calibration
- Enforce smooth gain solutions
- Discard outer clusters
- Simpler (better?) Cygnus A model

New ML-GPR
- Covariance from simulations
- Covariance depend on baseline
- Improved PS uncertainities



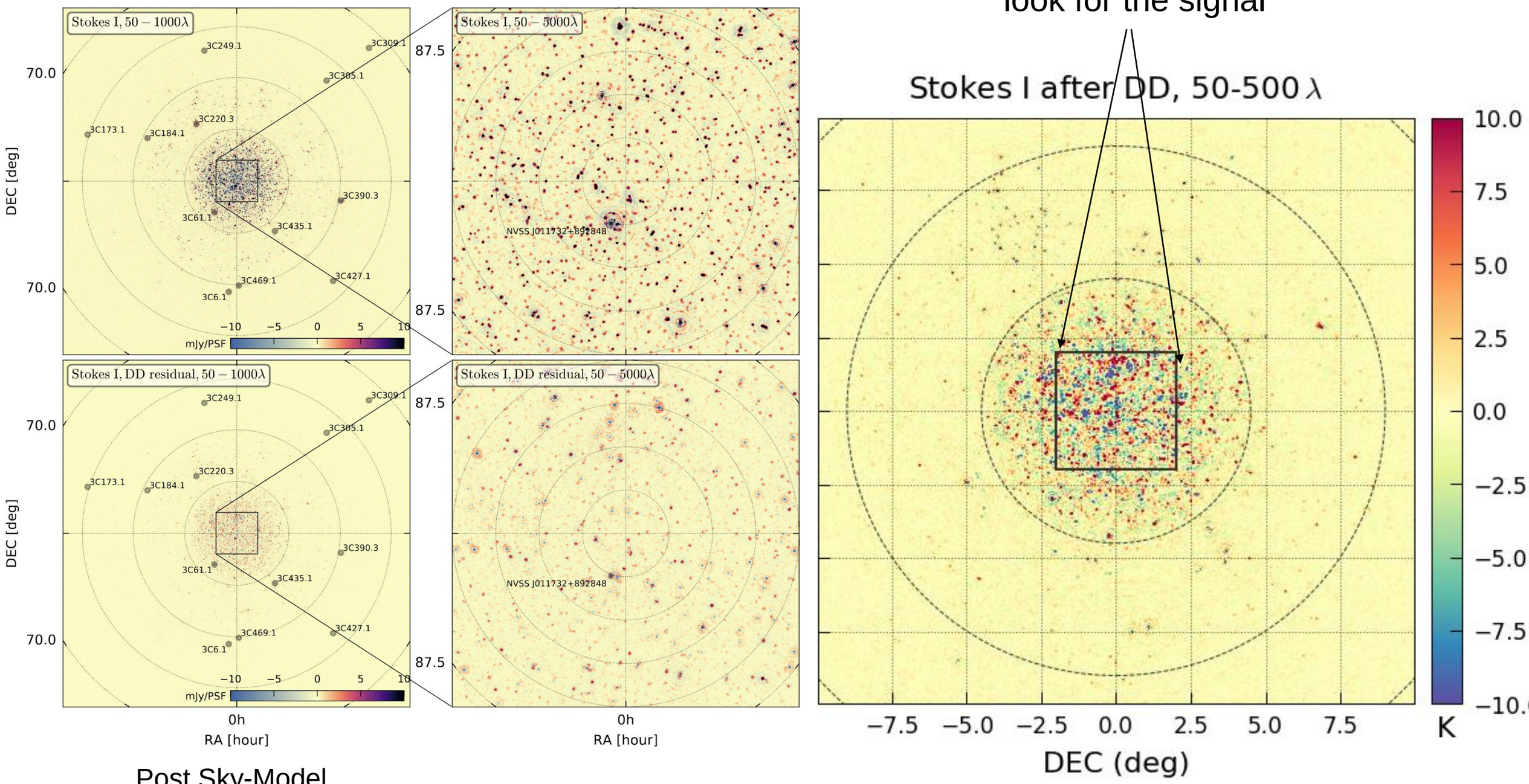
DD-gain Corrected Sky-Model Subtraction

NCP field, 140 hours, 134-146 MHz, z ~ 9.1

Wide-field Image

Zoom-in

Inner 4x4 where we look for the signal



Post Sky-Model Subtraction

Zoom-in

Mertens et al. 2020

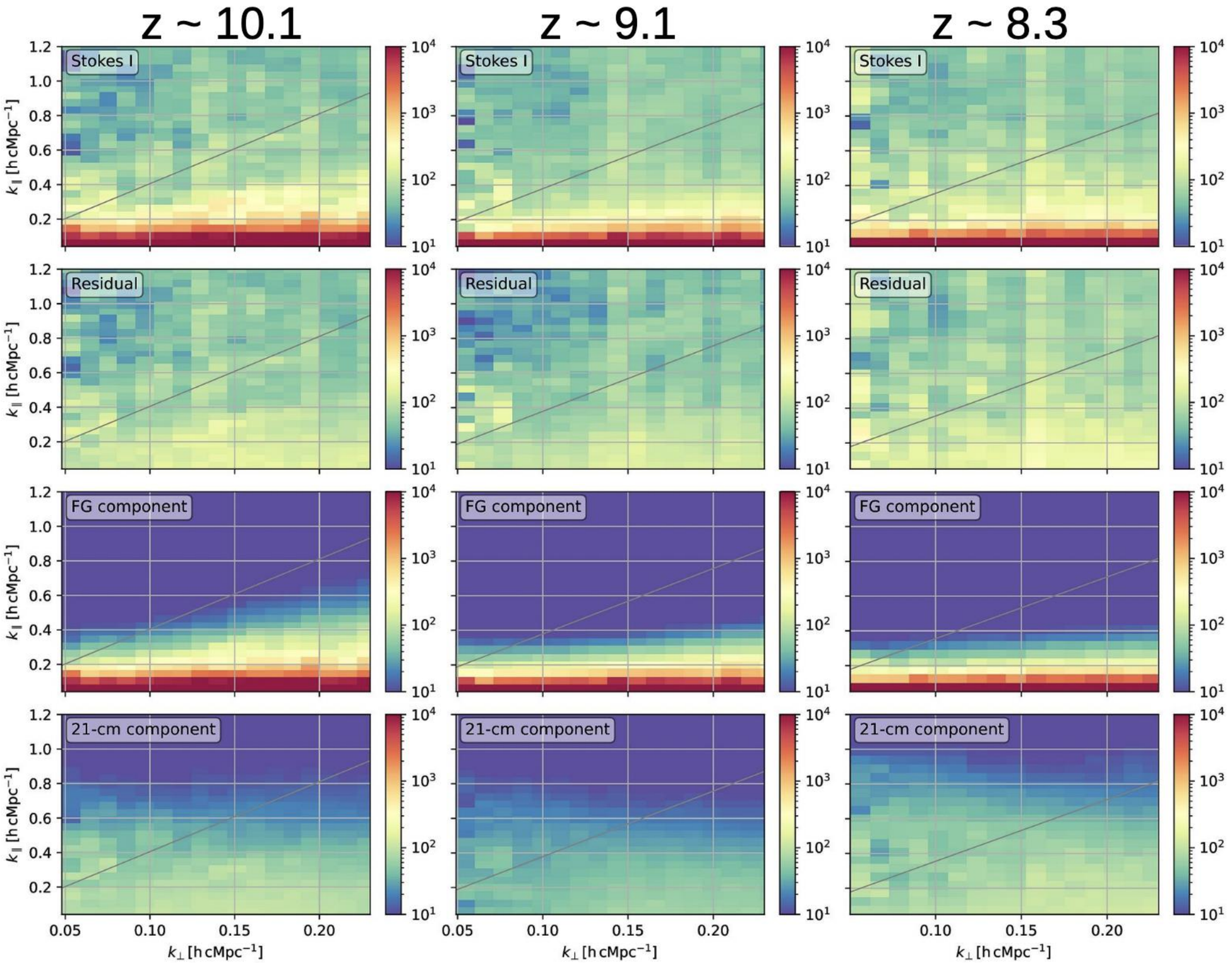
Gaussian Process Regression Signal Separation

Data
(minus sky-model)

Residuals

Foregrounds

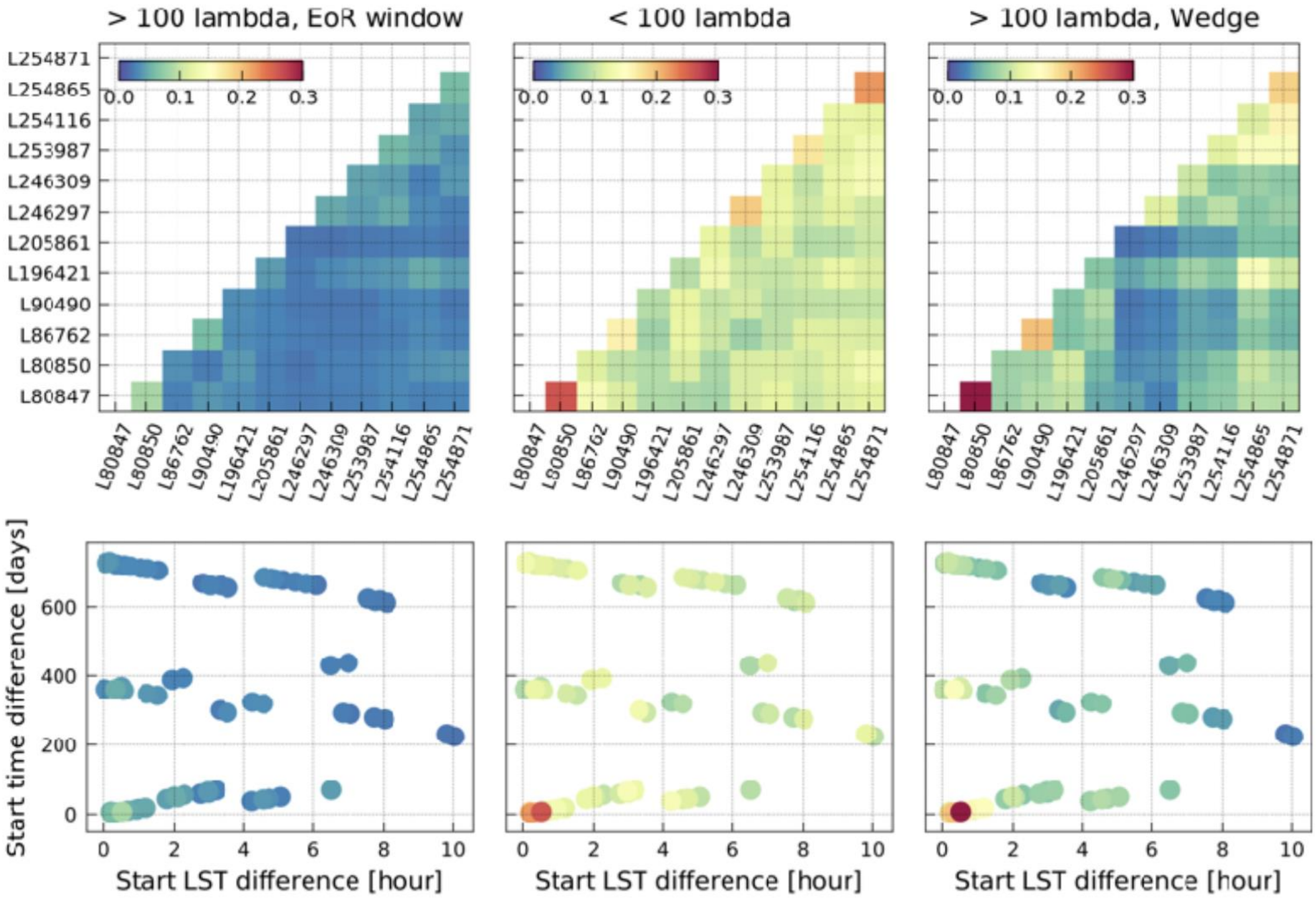
Rest
(incl. 21-cm signal
and “excess variance”)



Mevius & Mertens et al. 2023, in prep.

Power-Spectra — Night-to-night Correlations

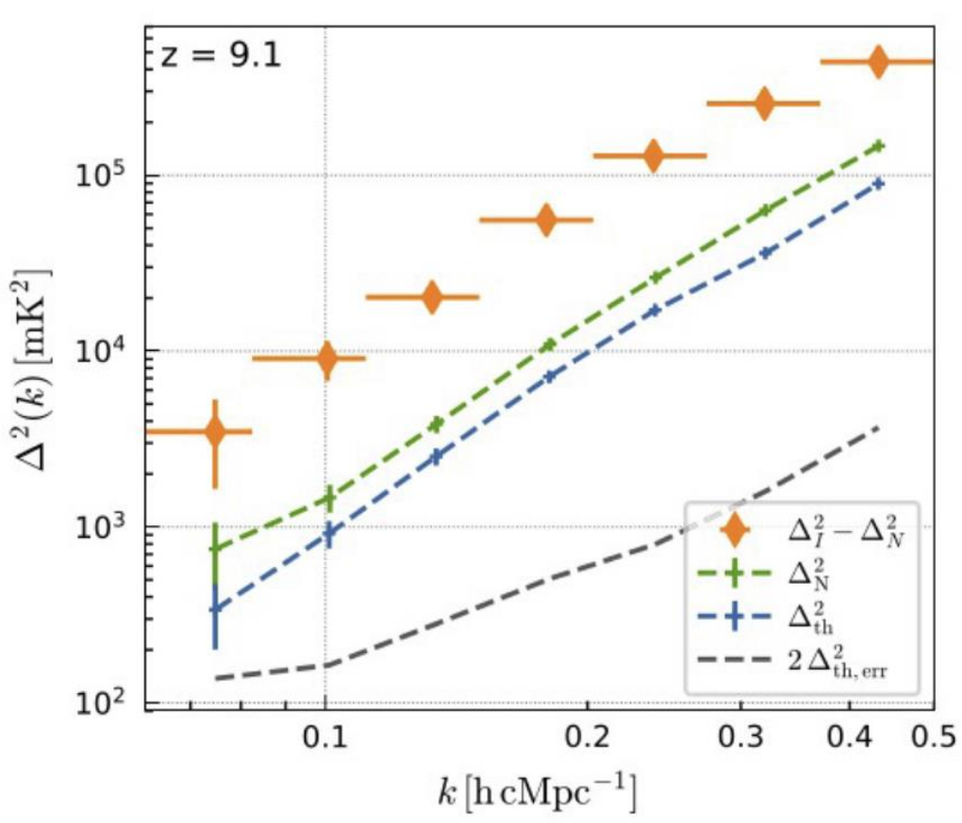
There are still correlations between nights. Closer correlation for nights starting at the same sidereal time: suggests that part of the sky still leaks through

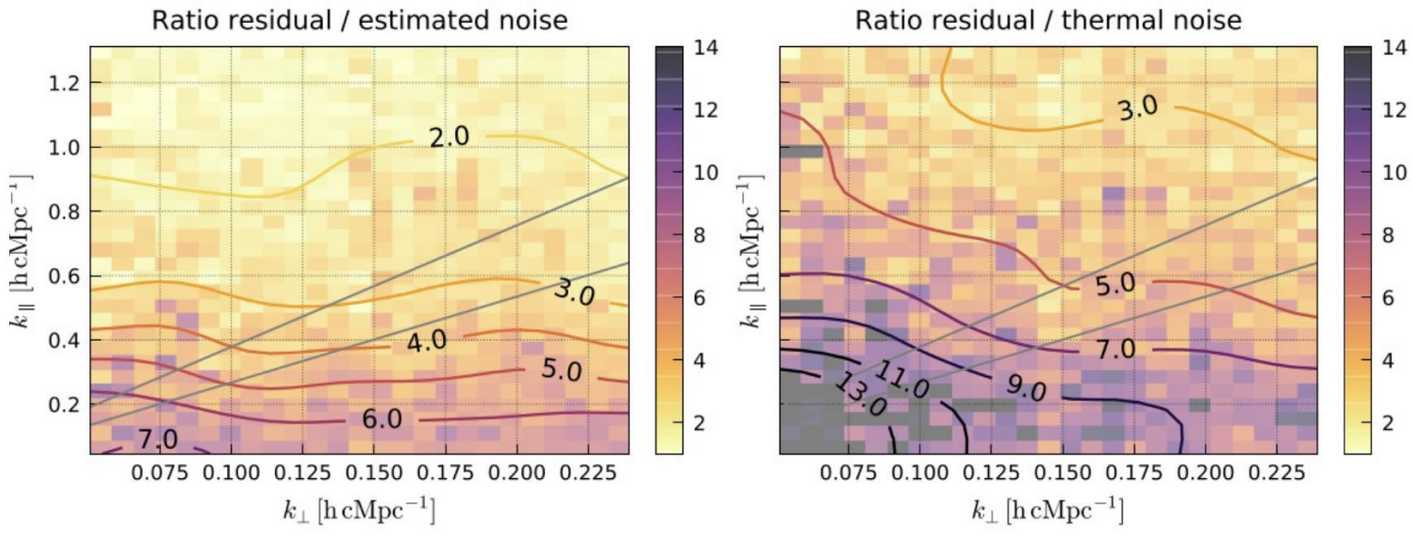


Mertens et al. (2020)

Earlier Results & Strategy

2017: we focused on three redshifts analysing 8 hours of data;
2020: we went “deep” by analysing 140hr nights for a single redshift;
2023: we go “deeper” by analysing 140hr nights for a three redshifts;





Excess variance (largely incoherence) is the main issues

Based on this — the then deepest 21-cm limit at z=9.1 — we published several papers with limits on the IGM temperature, and underlying sources.

Interpretations

Theory and Simulations

Constraining the intergalactic medium at $z \approx 9.1$ using LOFAR Epoch of Reionization observations

R. Ghara, S. K. Giri, G. Mellema, B. Ciardi, S. Zaroubi, I. T. Iliev, L. V. E. Koopmans, E. Chapman, S. Gazagnes, B. K. Gehlot, A. Ghosh, V. Jelić, F. G. Mertens, R. Mondal, J. Schaye, M. B. Silva, K. M. B. Asad, R. Kooistra, M. Mevius, A. R. Offringa, V. N. Pandey and S. Yatawatta

Monthly Notices of the Royal Astronomical Society, MNRAS 493, 4728–4747 (2020). Advance Access publication 2020 February 19. doi:10.1093/mnras/staa487

Accepted 2020 February 13. Received 2020 February 10; in original form 2019 December 20

We derive constraints on the thermal and ionization states of the intergalactic medium (IGM) at redshift ≈ 9.1 using new upper limits on the 21-cm power spectrum measured by the LOFAR radio telescope and a prior on the ionized fraction at that redshift estimated from recent cosmic microwave background (CMB) observations. We have used results from the reionization simulation code GRIZZLY and a Bayesian inference framework to constrain the parameters which describe the physical state of the IGM. We find that, if the gas heating remains negligible, an IGM with ionized fraction ≥ 0.13 and a full width at half-maximum (FWHM) $\geq 16\,h^{-1}$ Mpc is ruled out. For an IGM with a uniform spin temperature $T_S \gtrsim 3$ K, a characteristic size $\gtrsim 8\,h^{-1}$ comoving megaparsec (Mpc) and a full width at half-maximum no constraints on the ionized component can be computed. If the large-scale fluctuations of the signal are driven by spin temperature fluctuations, an IGM with a volume fraction ≤ 0.34 of heated regions with a temperature larger than CMB, average gas temperature 7–160 K, and a distribution of the heated regions with characteristic size 3.5–70 h^{-1} Mpc and FWHM of $\lesssim 110\,h^{-1}$ Mpc is ruled out. These constraints are within the 95 per cent credible intervals. With more stringent future upper limits from LOFAR at multiple redshifts, the constraints will become tighter and will exclude an increasingly large region of the parameter space.

Key words: radiative transfer – galaxies: formation – intergalactic medium – cosmology: theory – dark ages, reionization, first stars – X-rays: galaxies.

1 INTRODUCTION

The Epoch of Reionization (EoR) is one of the least understood chapters in the history of our Universe. The formation of the first luminous sources initiated the transition of the cold and neutral intergalactic medium (IGM) into a hot and ionized state. This transition had a significant impact on the later stages of structure formation through various feedback mechanisms (see e.g. Ciardi & Ferrara 2005 for a review). Although we know that reionization took place, very few facts about it are known with certainty (see e.g. Morales & Wyithe 2010; Pritchard & Loeb 2012; Zaroubi 2013; Barkana 2016, for reviews).

Theoretical models suggest that ionizing ultraviolet (UV) photons from the first sources created localized ionized regions, which over time grew in size, started to overlap and, as an increasing number of sources formed, led to a complete reionization of the IGM. Observations of high-redshift ($z \gtrsim 6$) quasar absorption spectra suggest that complete reionization was reached around redshift ≈ 6 (e.g. Fan et al. 2006; Mortlock et al. 2011; Venemans et al. 2015; Bañados et al. 2018). On the other hand, the measurement of the Thomson optical depth from the observation of cosmic microwave background (CMB) (Planck Collaboration VI 2018) suggests that the probable period of this event lies at redshift $\lesssim 10$ (Choudhury & Ferrara 2006; Mitra, Choudhury & Ferrara 2011, 2012). However, the details of the reionization process such as the exact timing of the EoR, the morphology of the H I distribution in the IGM, and the properties of early sources are still poorly known.

The redshifted 21-cm signal from neutral hydrogen in the IGM is the most promising probe of the EoR, as it has the ability to

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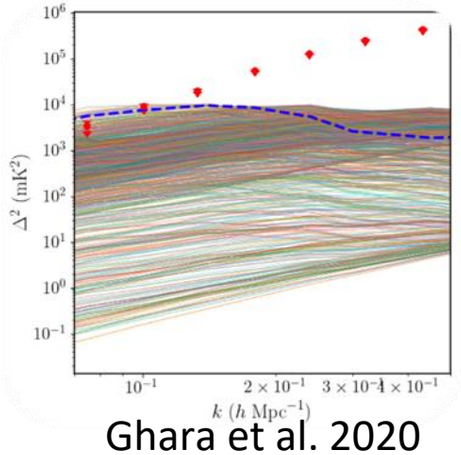
Very cold IGM models are excluded



Ghara et al. 2020

Tight Constraints on the Excess Radio Background at $z = 9.1$ from LOFAR

R. Mondal, A. Fialkov, C. Fling, I.T. Iliev, R. Barkana, B. Ciardi, G. Mellema, S. Zaroubi, L.V.E Koopmans, F. G. Mertens, B. K. Gehlot, R. Ghara, A. Ghosh, S. K. Giri and V.N. Pandey

MNRAS 000, 1–13 (2018). Preprint 3 April 2020. Compiled using MNRAS LaTeX style file v3.0

The ARCADE2 and LWA1 experiments have claimed an excess over the Cosmic Microwave Background (CMB) at low radio frequencies. If the cosmological high-redshift contribution to this radio background is between 0.1% and 22% of the CMB at 1.42 GHz, it could explain the tentative EDGES Low-Band detection of the anomalously deep absorption in the 21-cm signal of neutral hydrogen (Fialkov & Barkana 2019). We use the upper limit on the 21-cm signal from the Epoch of Reionization ($z = 9.1$) based on 141 hours of observations with LOFAR (Mertens et al. 2020) to evaluate the contribution of the high redshift Universe to the detected radio background. Marginalizing over astrophysical properties of star-forming halos, we find (at 68% C.L.) that the cosmological radio background can be at most 0.7% of the CMB at 1.42 GHz. This limit rules out strong contribution of the high-redshift Universe to the ARCADE2 and LWA1 measurements. Even though LOFAR places limit on the extra radio background, excess of 0.1 – 0.7% over the CMB (at 1.42 GHz) is still allowed and could explain the EDGES Low-Band detection. We also constrain the thermal and ionization state of the gas at $z = 9.1$, and put limits on the properties of the first star-forming objects. We find that, in agreement with the limits from EDGES High-Band data, LOFAR data disfavour scenarios with inefficient X-ray sources and cases where the Universe was ionized by massive halos only.

Key words: cosmology: theory – dark ages, reionization, first stars –diffuse radiation – methods: statistical

1 INTRODUCTION

Studies of the Epoch of Reionization (EoR) and Cosmic Dawn are key to understanding early galaxy formation and the evolution of the Intergalactic Medium (IGM) (see e.g. review by Barkana & Loeb 2001; Furlanetto et al. 2006).

Ionising properties of the high-redshift sources are currently largely constrained by the measurement of the electron scattering optical depth, τ_e estimated by Planck (e.g. Planck Collaboration et al. 2018), Ly-α damping wing absorption in the spectra of the high-redshift quasars (e.g., Greig et al. 2017, 2019) and Ly-α emission from Lyman Break galaxies (Mason et al. 2018). Accumulating evidence supports rapid and late reionization completed by $z \sim 6$ (e.g., Weinberger et al. 2019). However, these observations

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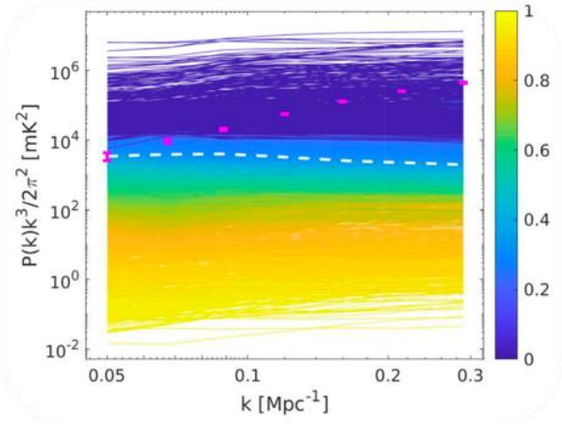
Strong excess radio-background models are excluded



Mondal et al. 2020

Interpreting LOFAR 21-cm signal upper limits at $z \approx 9.1$ in the context of high-z galaxy and reionisation observations

Bradley Greig, Andrei Mesinger, Léon V. E. Koopmans, Benedetta Ciardi, Garrelt Mellema, Saleem Zaroubi, Sambit K. Giri, Raghunath Ghara, Abhik Ghosh, Ilian T. Iliev, Florent G. Mertens, Rajesh Mondal, André R. Offringa, Vishambhar N. Pandey

MNRAS 000, 000–000 (0000). Preprint 8 June 2020. Compiled using MNRAS LaTeX style file v3.0

Using the latest upper limits on the 21-cm power spectrum at $z \approx 9.1$ from the Low Frequency Array (LOFAR), we explore regions of parameter space which are inconsistent with the data. We use 21CMMC, a Monte Carlo Markov Chain sampler of 21CMFAST which directly forward models the 3D cosmic 21-cm signal in a fully Bayesian framework. We use the astrophysical parameterisation from 21CMFAST, which includes mass-dependent star formation rates and ionising escape fractions as well as soft-band X-ray luminosities to place limits on the properties of the high-z galaxies. Further, we connect the disfavoured regions of parameter space with existing observational constraints on the Epoch of Reionisation such as ultra-violet (UV) luminosity functions, background UV photoionisation rate, intergalactic medium (IGM) neutral fraction and the electron scattering optical depth. We find that all models exceeding the 21-cm signal limits set by LOFAR at $z \approx 9.1$ are excluded at $\geq 2\sigma$ by other probes. Finally, we place limits on the IGM spin temperature from LOFAR, disfavouring at 95 per cent confidence spin temperatures below ~ 2.6 K across an IGM neutral fraction range of $0.15 \lesssim x_{\rm HI} \lesssim 0.6$. Note, these limits are only obtained from 141 hrs of data in a single redshift bin. With tighter upper limits, across multiple redshift bins expected in the near future from LOFAR, more viable models will be ruled out. Our approach demonstrates the potential of forward modelling tools such as 21CMMC in combining 21-cm observations with other high-z probes to constrain the astrophysics of galaxies.

Key words: cosmology: theory – dark ages, reionisation, first stars – diffuse radiation – early Universe – galaxies: high-redshift – intergalactic medium

1 INTRODUCTION

The Epoch of Reionisation (EoR) corresponds to the final major baryonic phase change of the Universe. This occurs when the once cold, neutral hydrogen that permeated the

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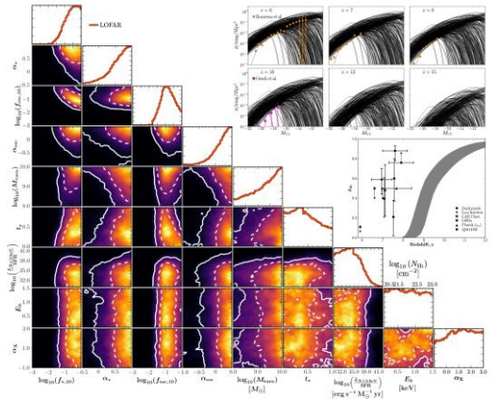
Astrophysical models

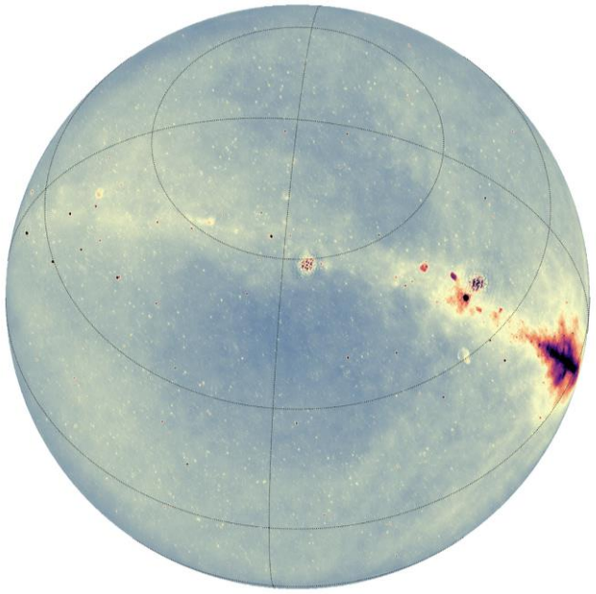


Greig et al. 2020

The Data Analysis Improvements

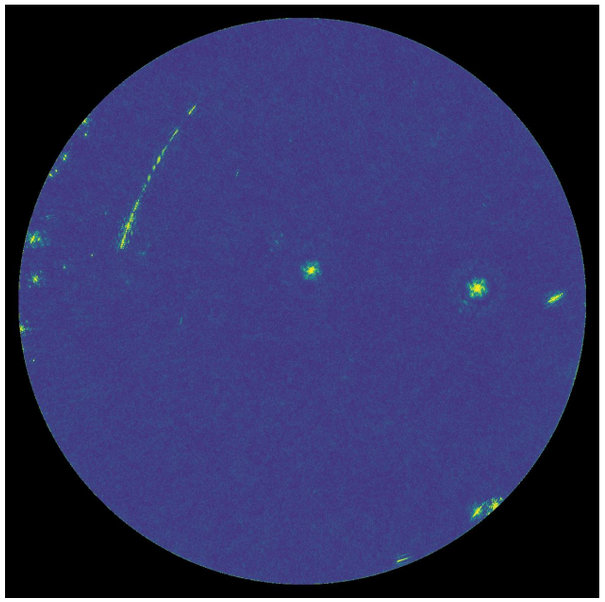
Bright Foregrounds/ Full-Stokes Sky Models

Gehlot et al. 2020



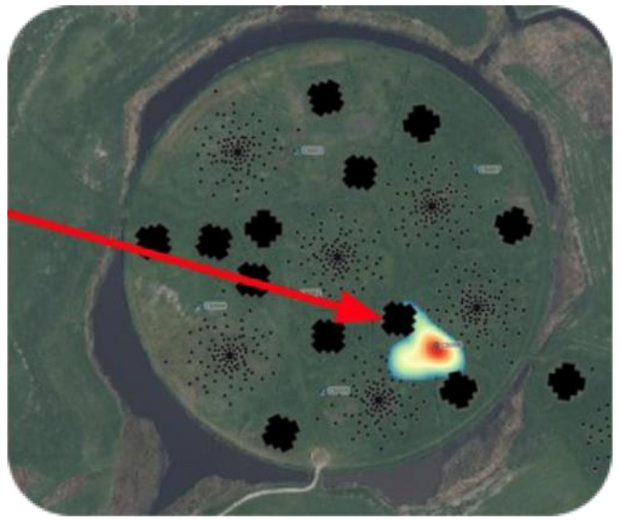
Radio Frequency Interference Mitigation

Gehlot et al. 2023



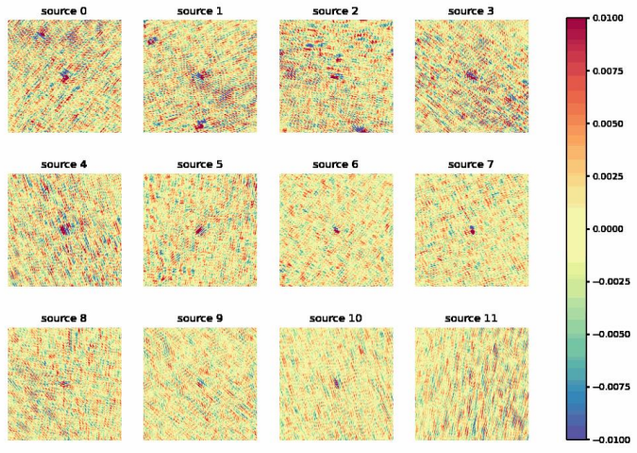
Near-Field RFI Imaging

Credit: Mevius & Mertens



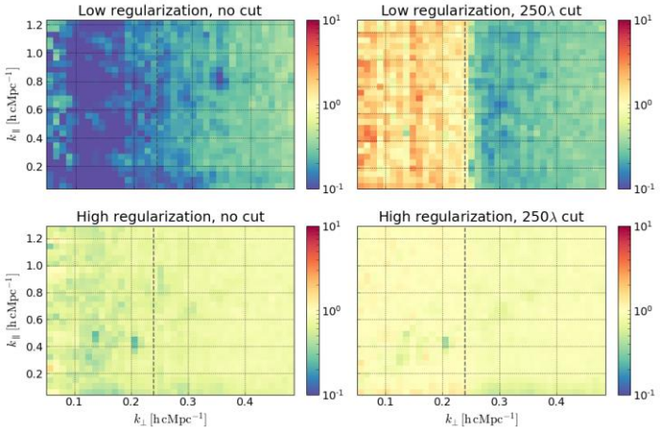
Ionospheric Refraction Diffraction

Credit: Brackenhoff



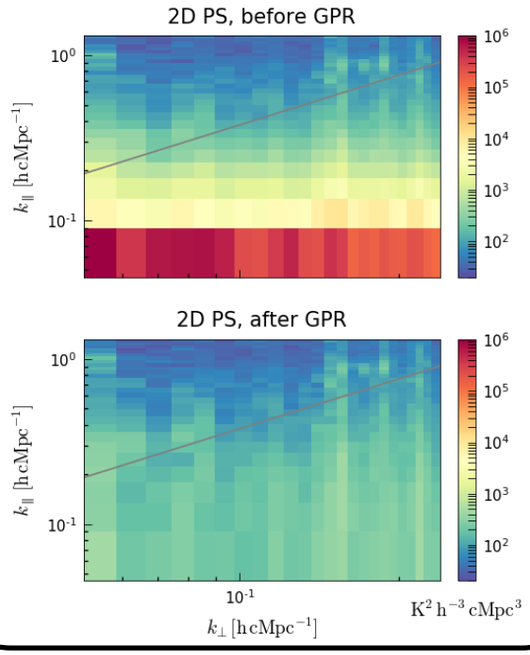
Frequency/Direction-Dependent Calibration

Mevius et al. 2022



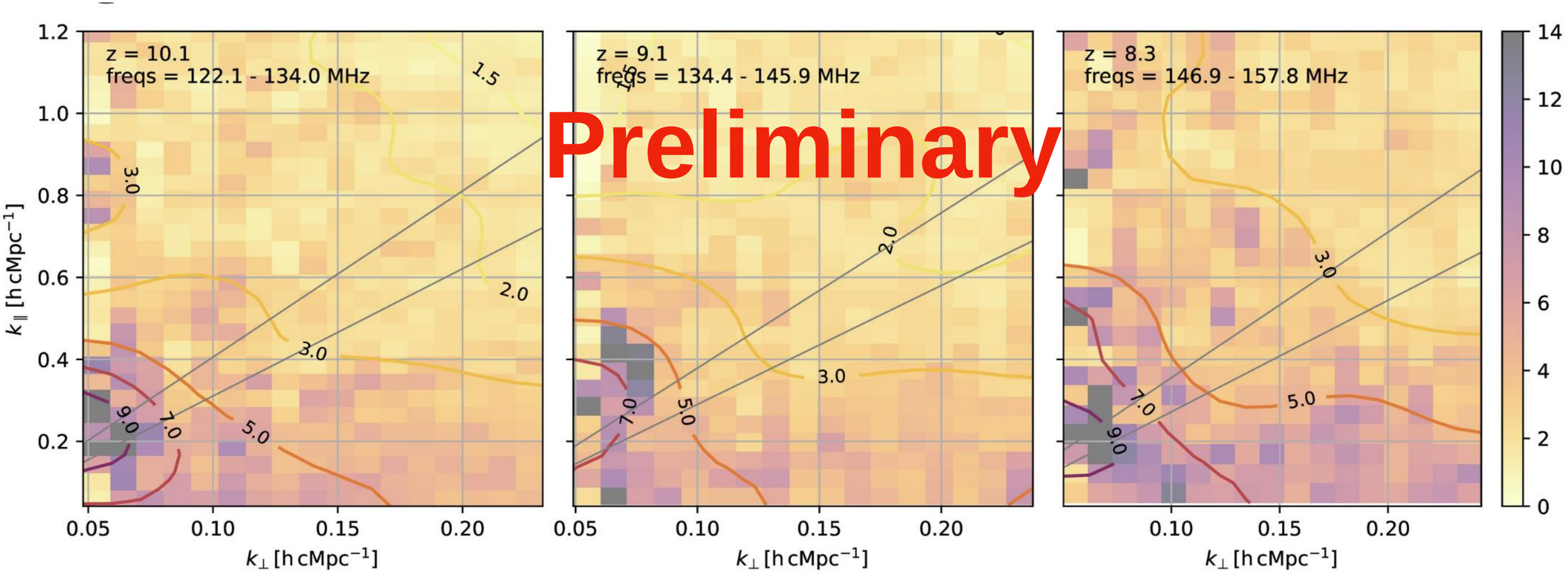
GPR Data Modelling

Mertens et al.



Where do we currently stand? (2023)

Considerable Improvements in reducing the **Excess Variance**



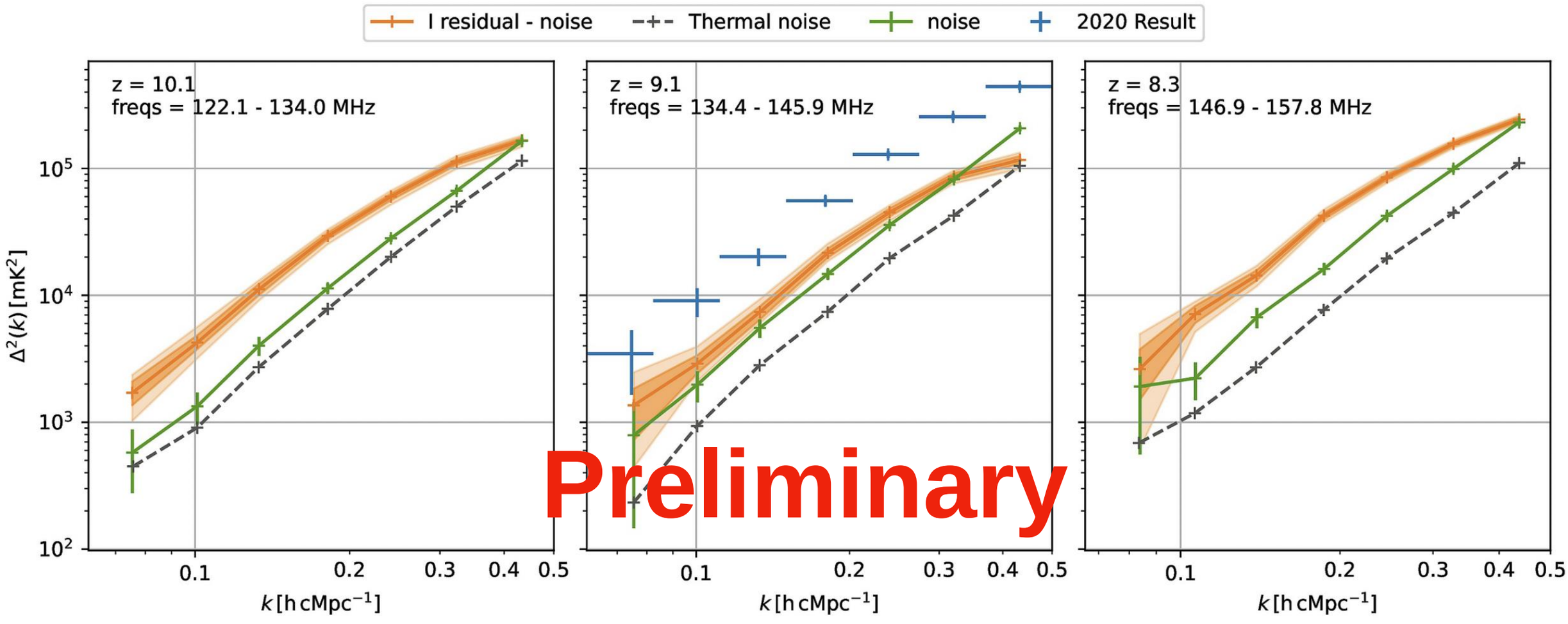
Still the dominant source of noise, but considerably lower than in the 2020 & 2017 analyses: better RFI excision, DI/DD calibration, sky-models, residual FG removal.

Probably now dominated by sources in the far-field that vary due to beam.

Image credit: Mertens

Where do we currently stand? (2023)

Based on these improvements, we are reprocessed 140 hrs of data reaching 2x deeper levels with same data and expanded to 3 redshifts.



Next steps: with the new 1+ petaflop CoDEX GPU cluster, we plan to process ~500 hrs of data in the coming ~1 year.

Image credit: Mertens

Where do we currently stand? (2023)

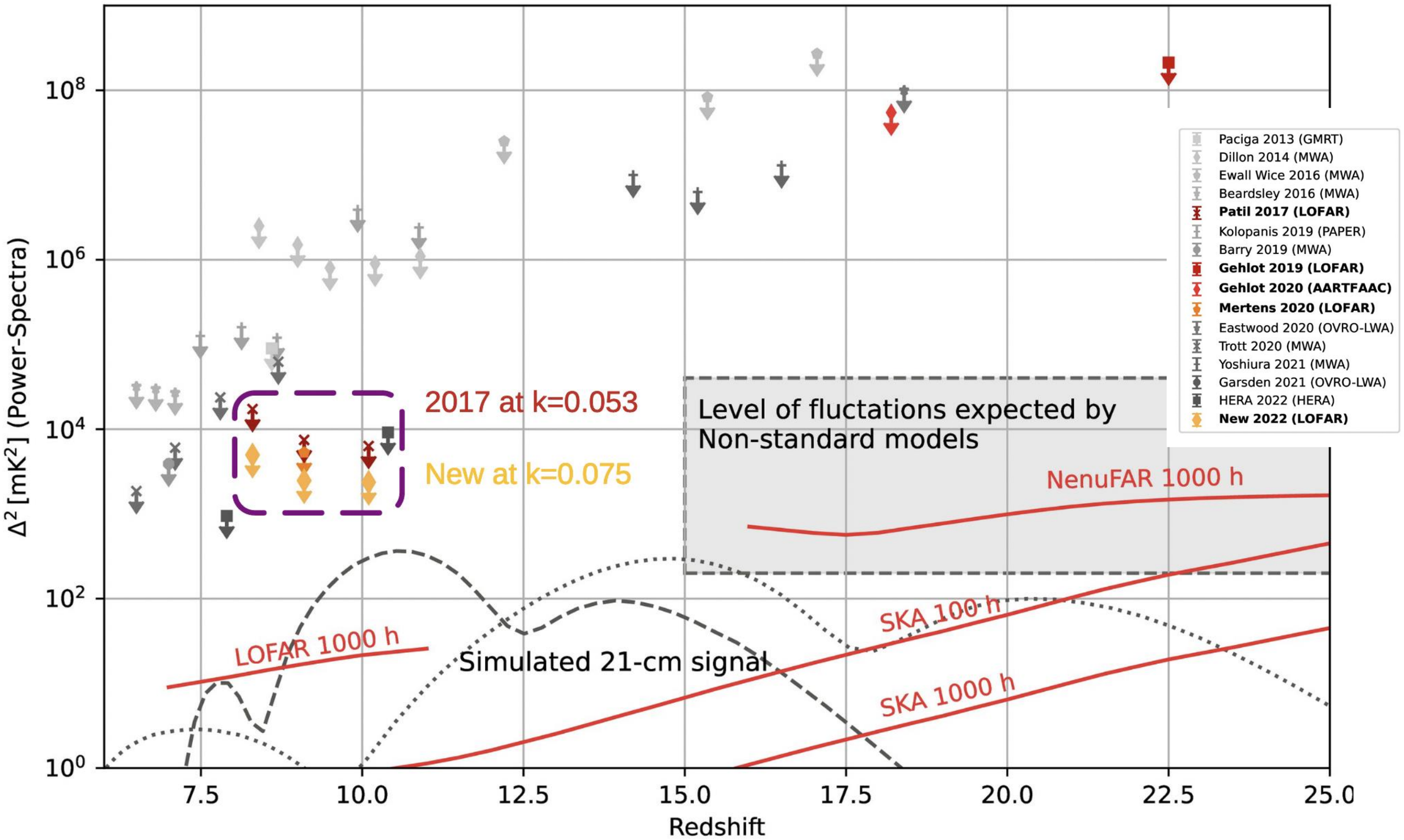


Image credit: Mertens

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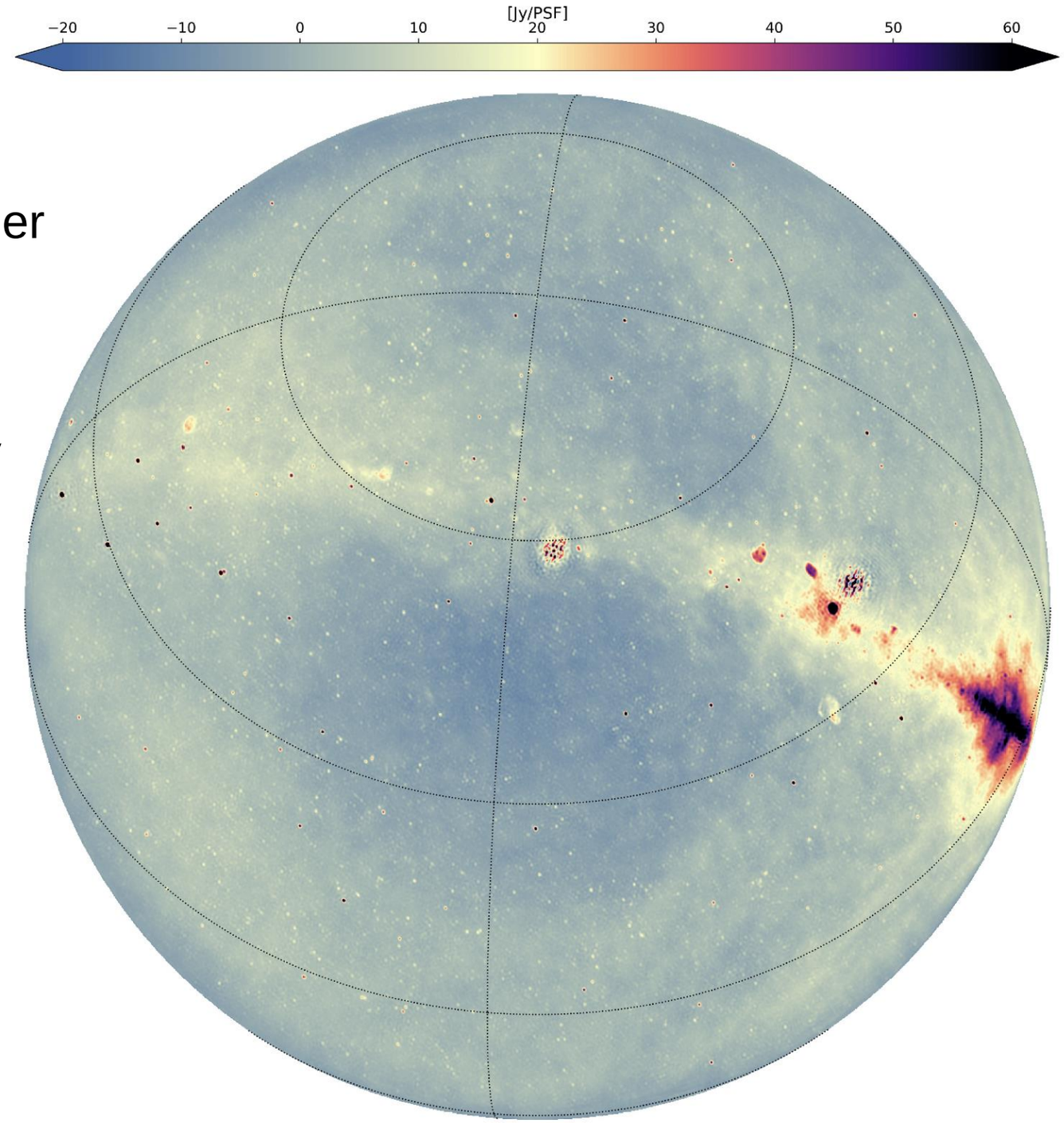
LOFAR-AARTFAAC Cosmic Explorer Programme

LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

LOFAR-AARTFAAC Cosmic Explorer

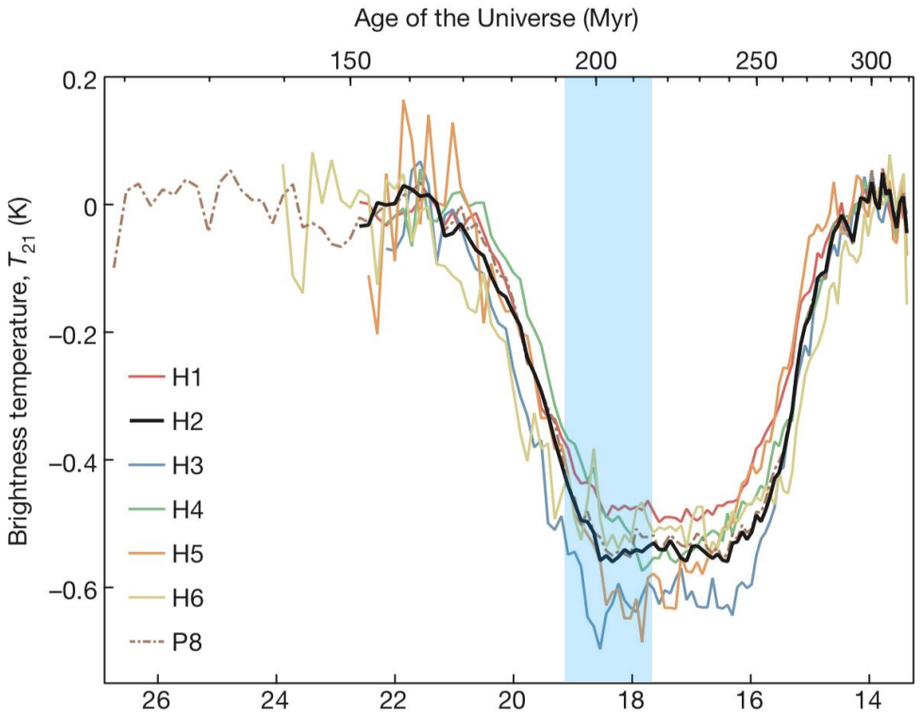


AARTFAAC

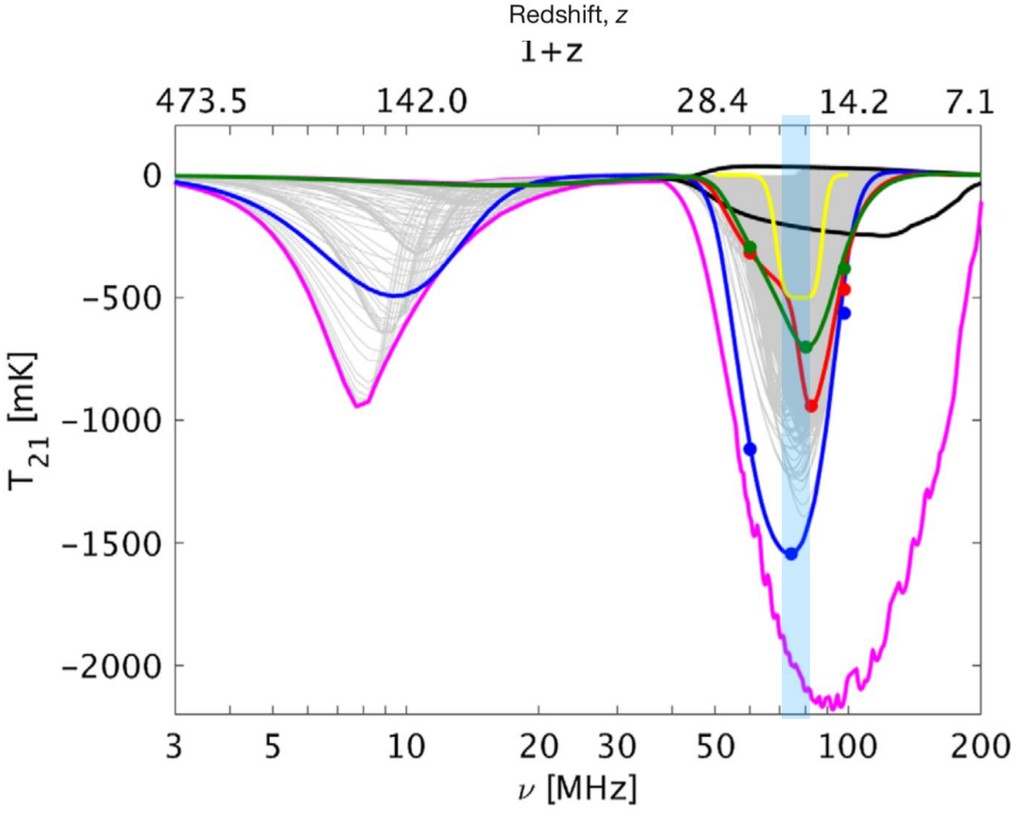
- Cross-correlation all dipoles/tiles of inner 6-12 stations (576 receivers)
- Full sky/beam field of view (LBA/HBA)
- Build originally for transients
- Limited BW due to correlators capacity

- PIs: Gehlot & Koopmans

LOFAR-AARTFAAC Cosmic Explorer



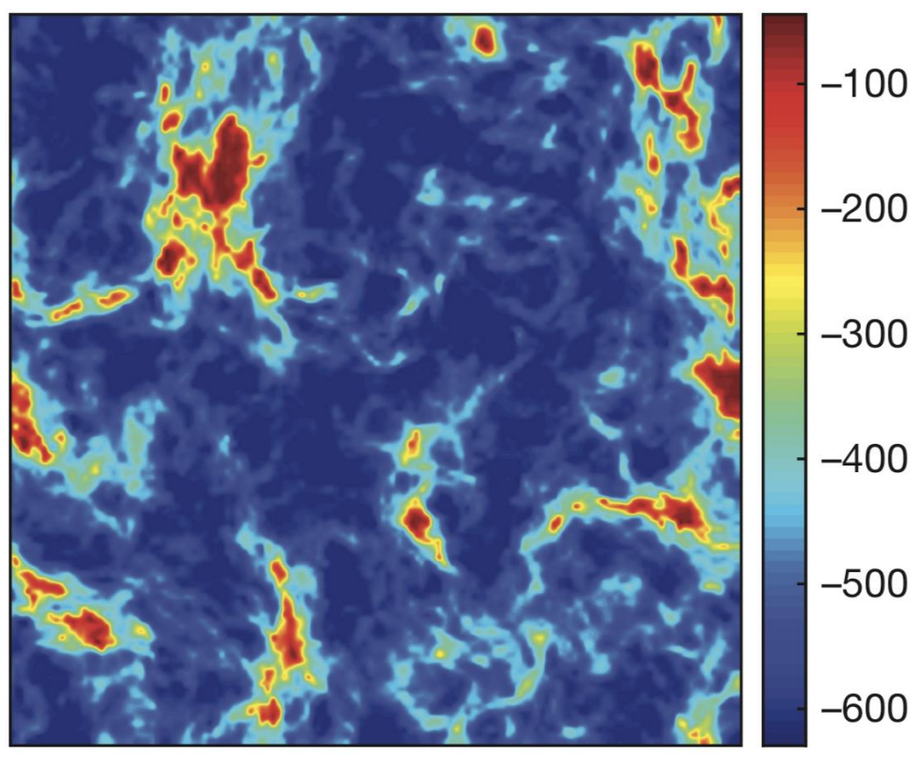
Bowman et al. 2018



Fialkov et al. 2018

Aim: Exclude or detect power spectra
Δ_{21}~0.1-1K @ k~0.1 cMpc^{-1} @ z~18

- In hand: 500 hrs of LOFAR-LBA data
- Cross-correlating 576 dipoles; all-sky FoV
- z~18 (72-75MHz; medium BW)
- Some signal strengths require 50x less integration time than standard models.

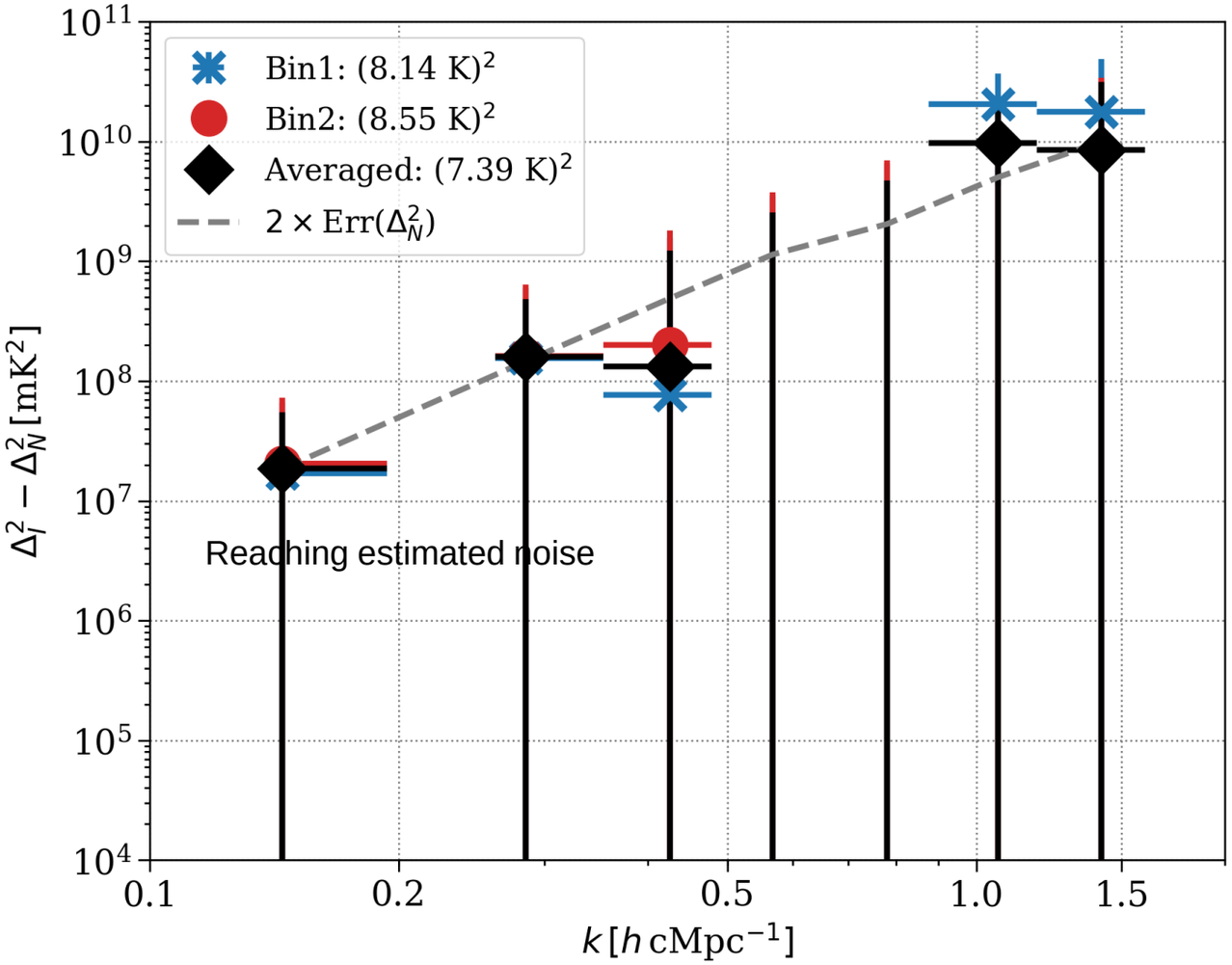


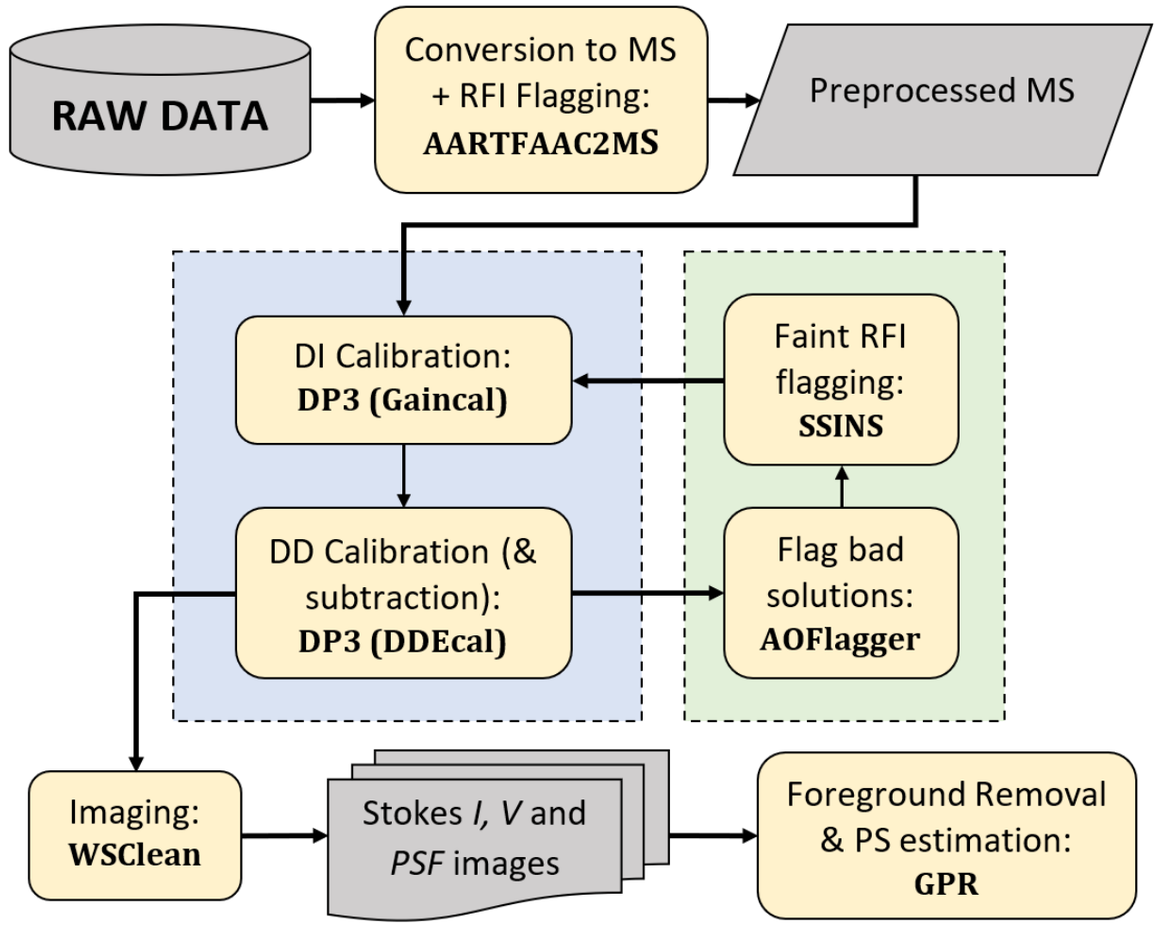
Barkana et al. 2018

LOFAR-AARTFAAC Cosmic Explorer

In 2020, the first limits at z~18 from ~2 hr of data

- Semi-driftscan (15 min each)
- Sky-model: Cas A, Cyg A
- Direction-independent calibration only
- Limited RFI flagging



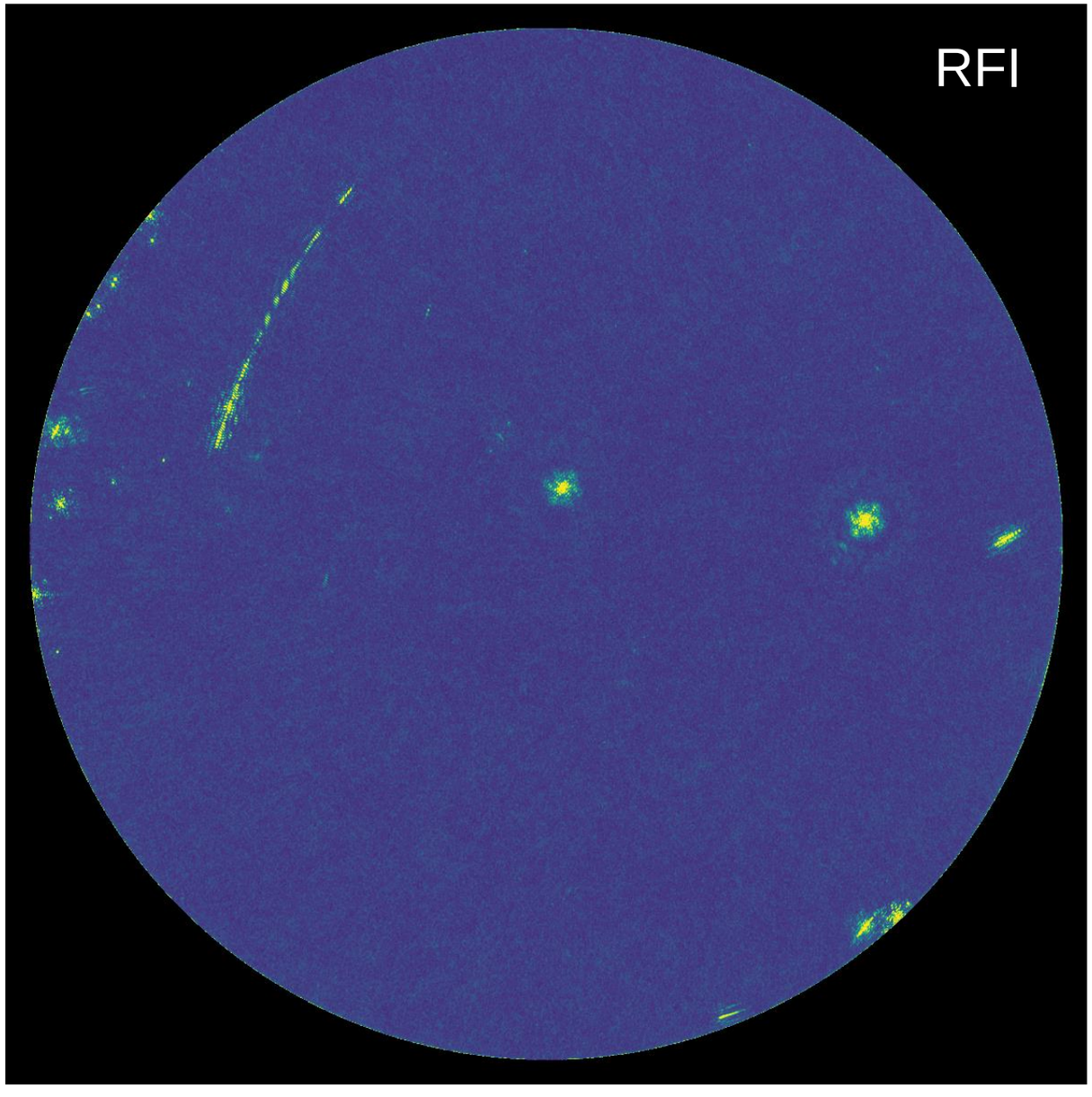


"Simple" Processing Scheme in 2020

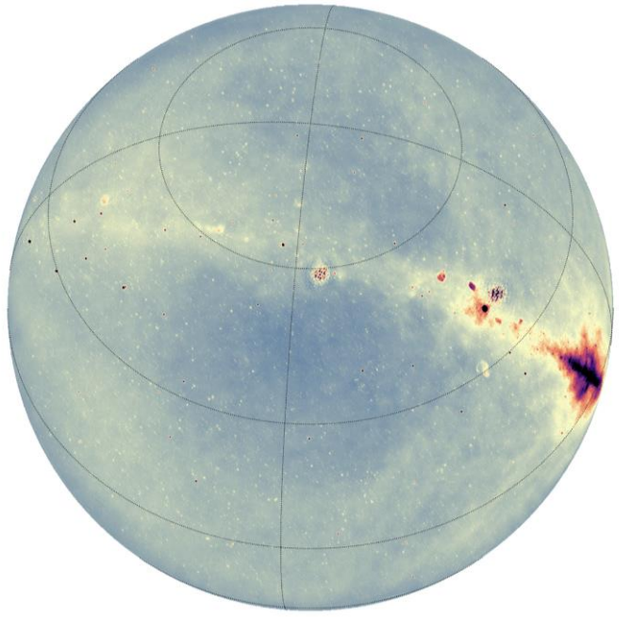
Gehlot et al. (2020)

ACE: Challenges of Wide-Field Low-Frequency Imaging

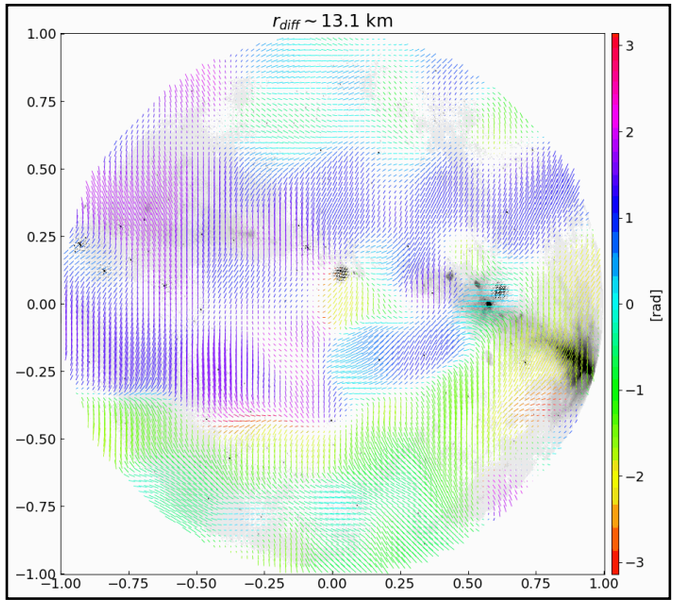
Increasing level of challenges of an all-sky low-frequency experiment:
Excellent lessons for low-frequency wide-field arrays (e.g. ALO/SKA-low)



Extended Foregrounds

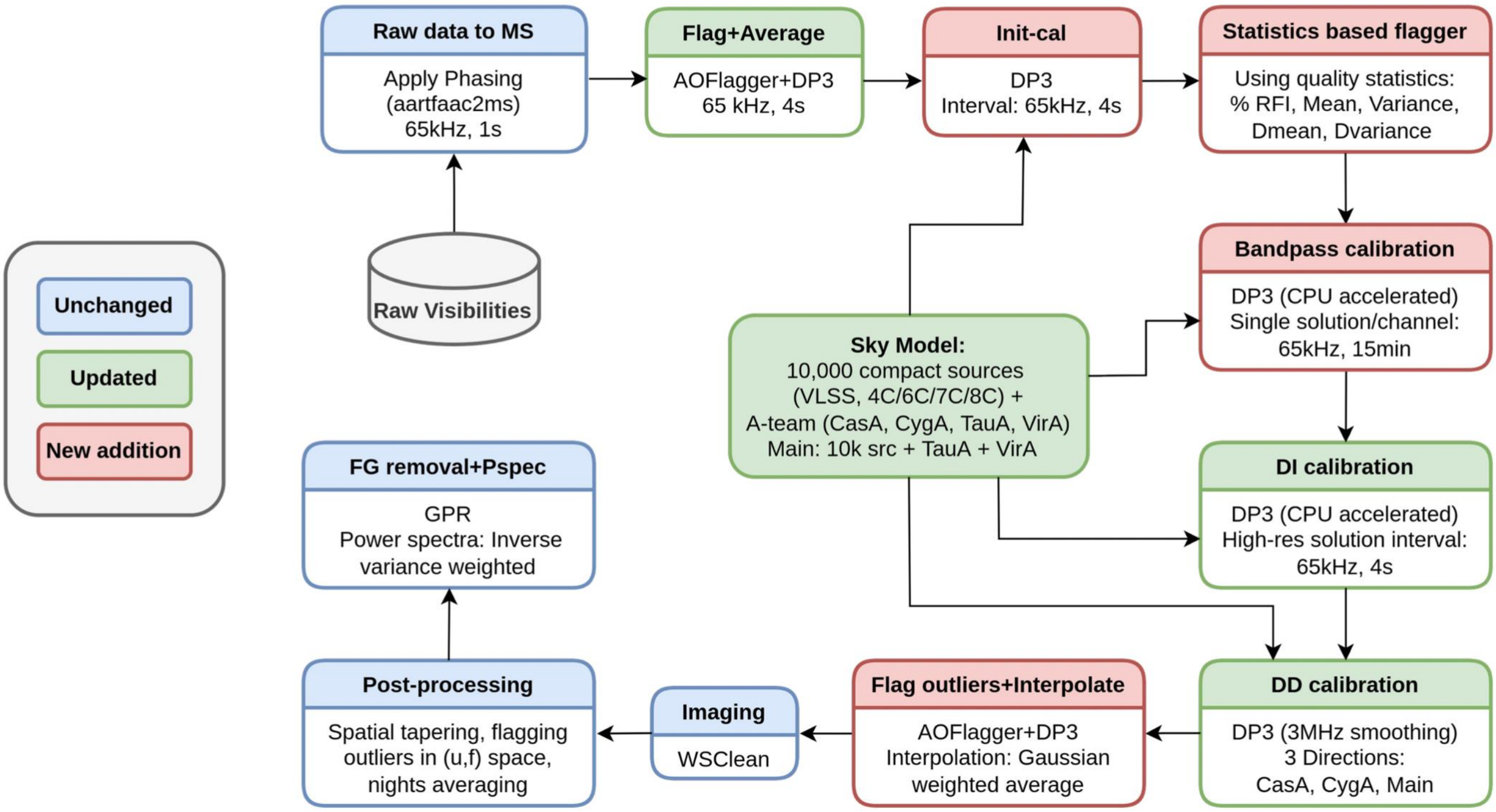


Ionosphere



ACE: Challenges of Wide-Field Low-Frequency Imaging

In 2023, significant progress has been made on the same 2 hours of data (of 500 hr in hand) and processing has been improved drastically.

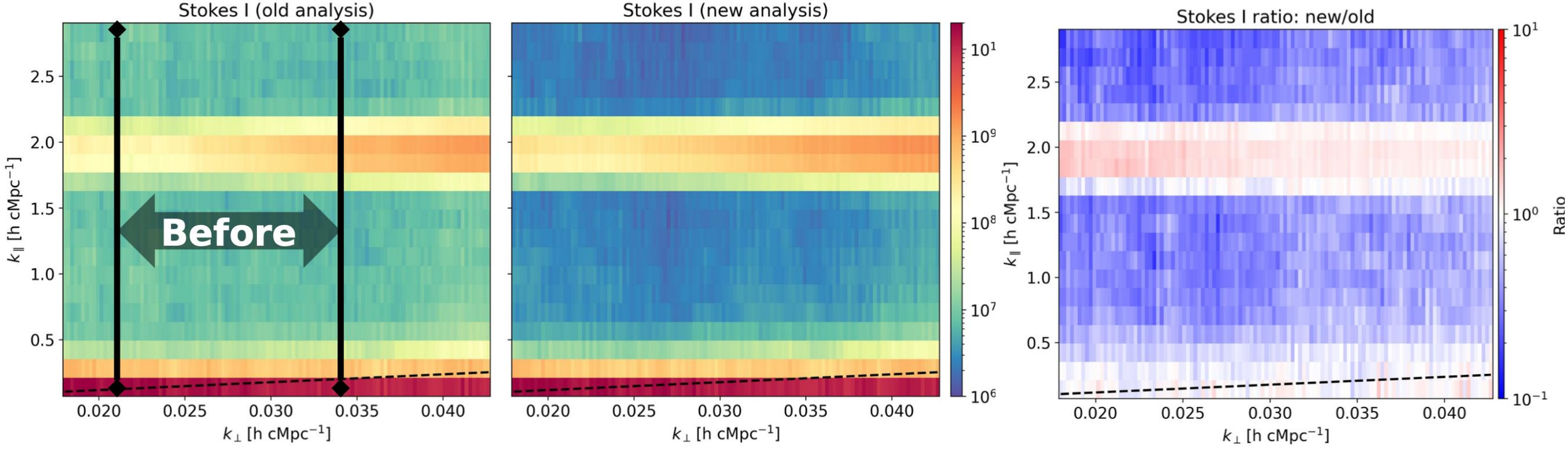


ACE: New Result in 2023

In 2023, significant progress on the same 2 hours of data (of 500 hr in hand).

- Improved sky-model: 10,000 components rather than just 2 (Cas/Cyg)
- Improved RFI excision: several levels (pre-post calibration)
- Improved DI+DD cal. (DD-calibration instead of just DI calibration)
- etc.

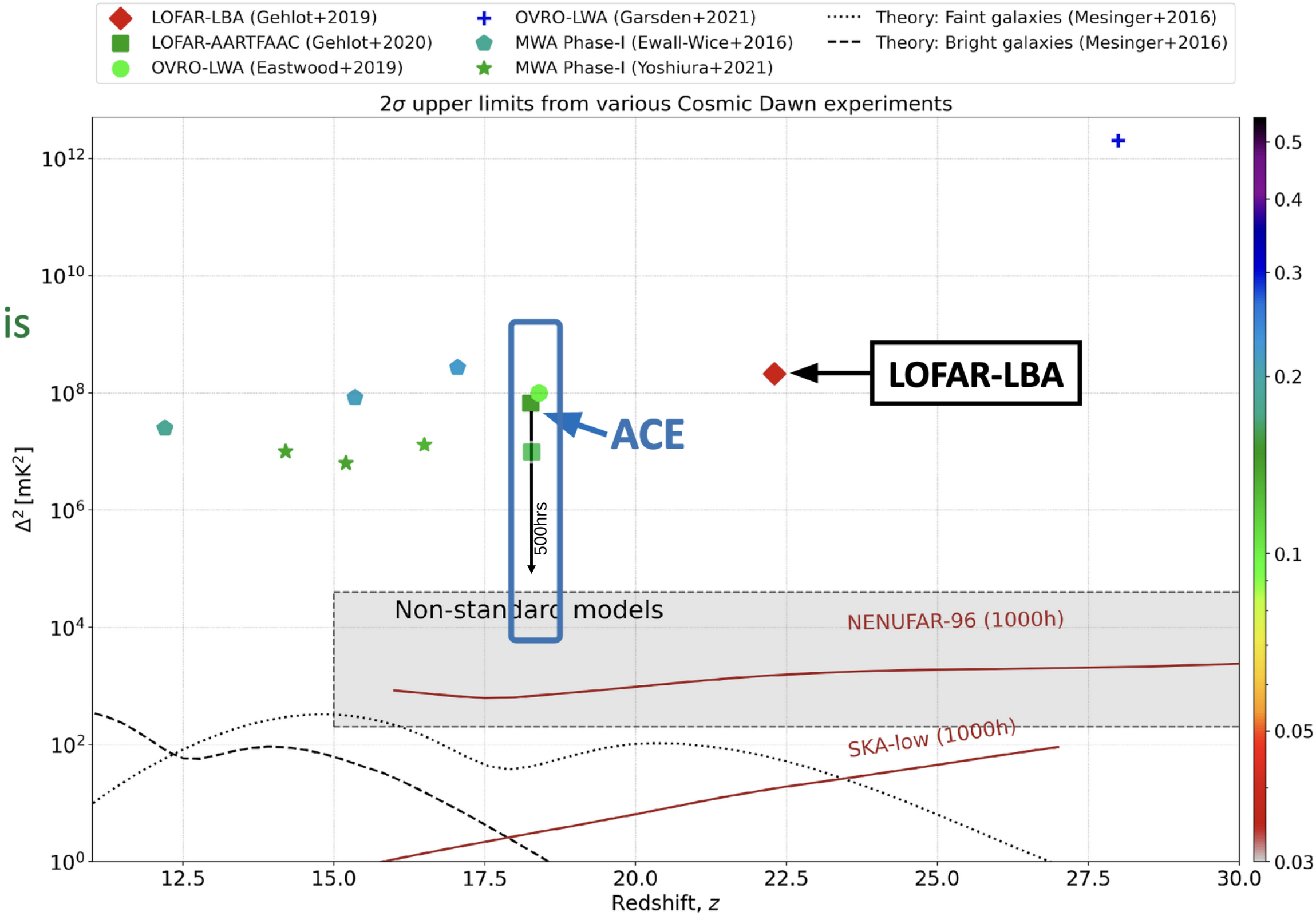
OLD ANALYSIS **NEW ANALYSIS** **RATIO**



Gain by factor ~3 on same data

Gehlot et al. in prep

LOFAR-AARTFAAC Cosmic Explorer



is

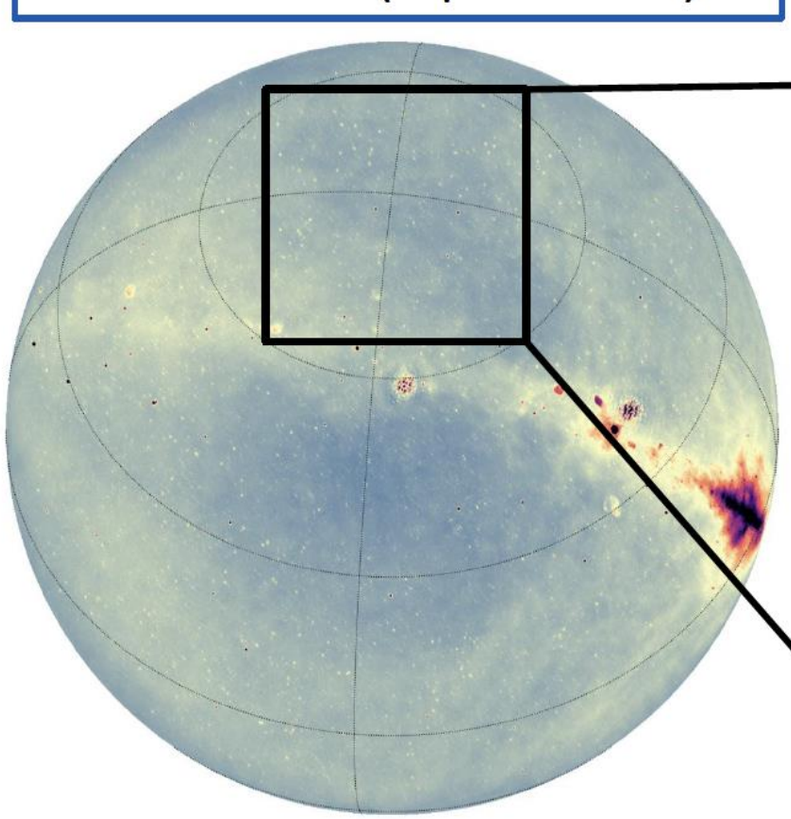
The Epoch of Reionization and beyond with the AARTFAAC REionization Survey: ARES

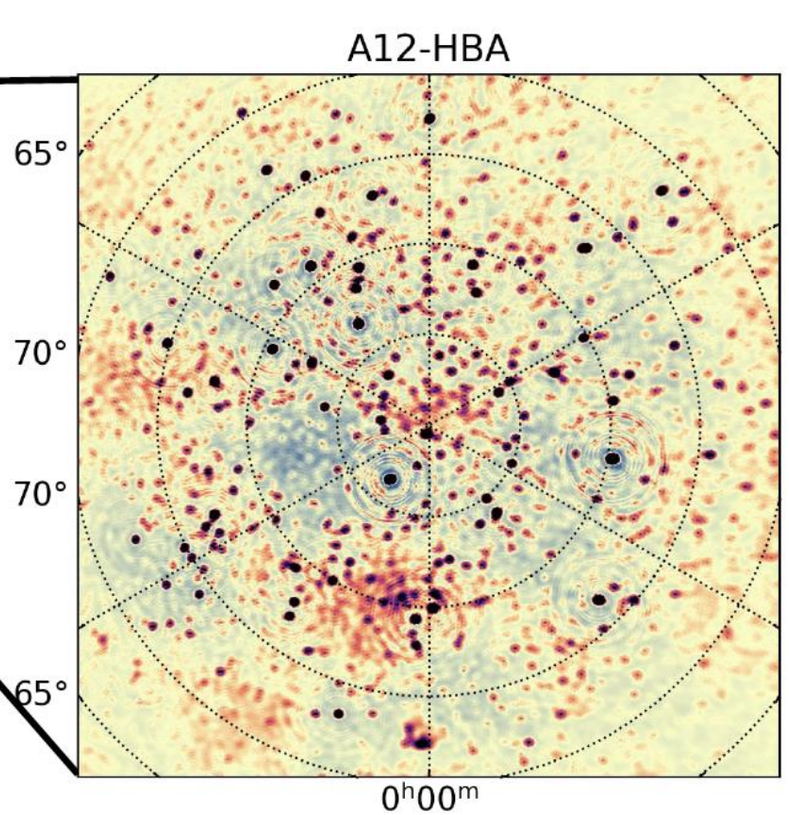
Proposed observational program with LOFAR-HBA at tile-level (AARTFAAC) to (i) measure the 21-cm signal on ultra-large scales and over much larger volume (increase survey speed by factor ~5) and (iii) create a full Norther Sky Diffuse Sky (Polarised) model using HBA and LBA observations.

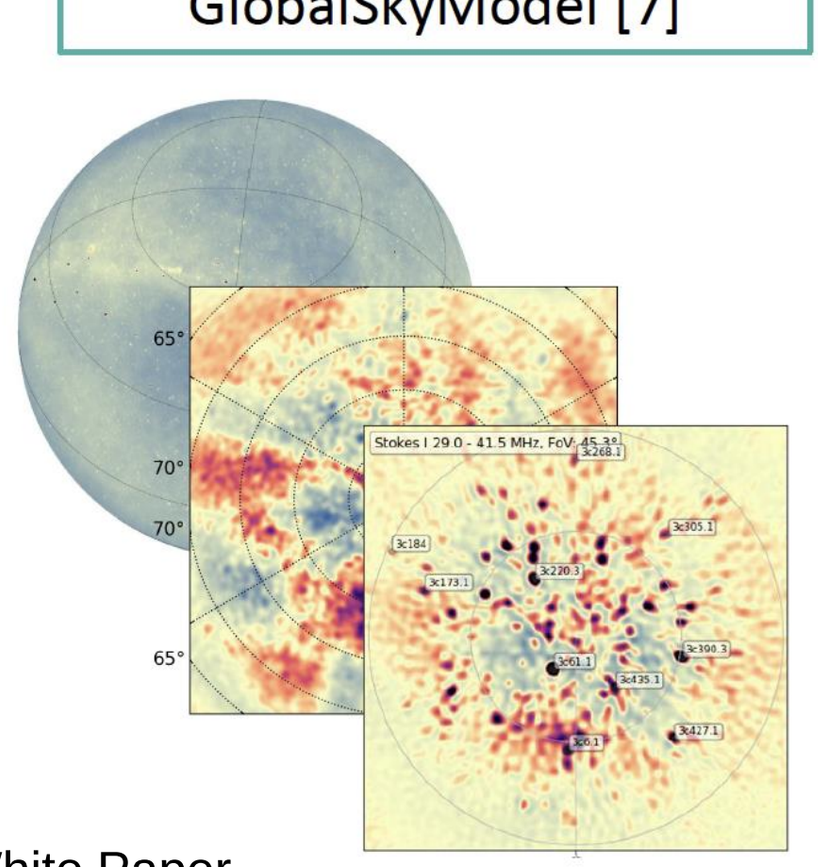
Tier 1: Spherical harmonics /m-mode imaging with AARTFAAC (dipole level)

Tier 2: Tile level imaging with AARTFAAC/NenuFAR

Tier 3: Combine high and low frequency radio maps and incorporate into the GlobalSkyModel [7]







Gehlot et al. (Dec. 2021) Expression of Interest White Paper

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NenuFAR Cosmic Dawn Key Science Programme

LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

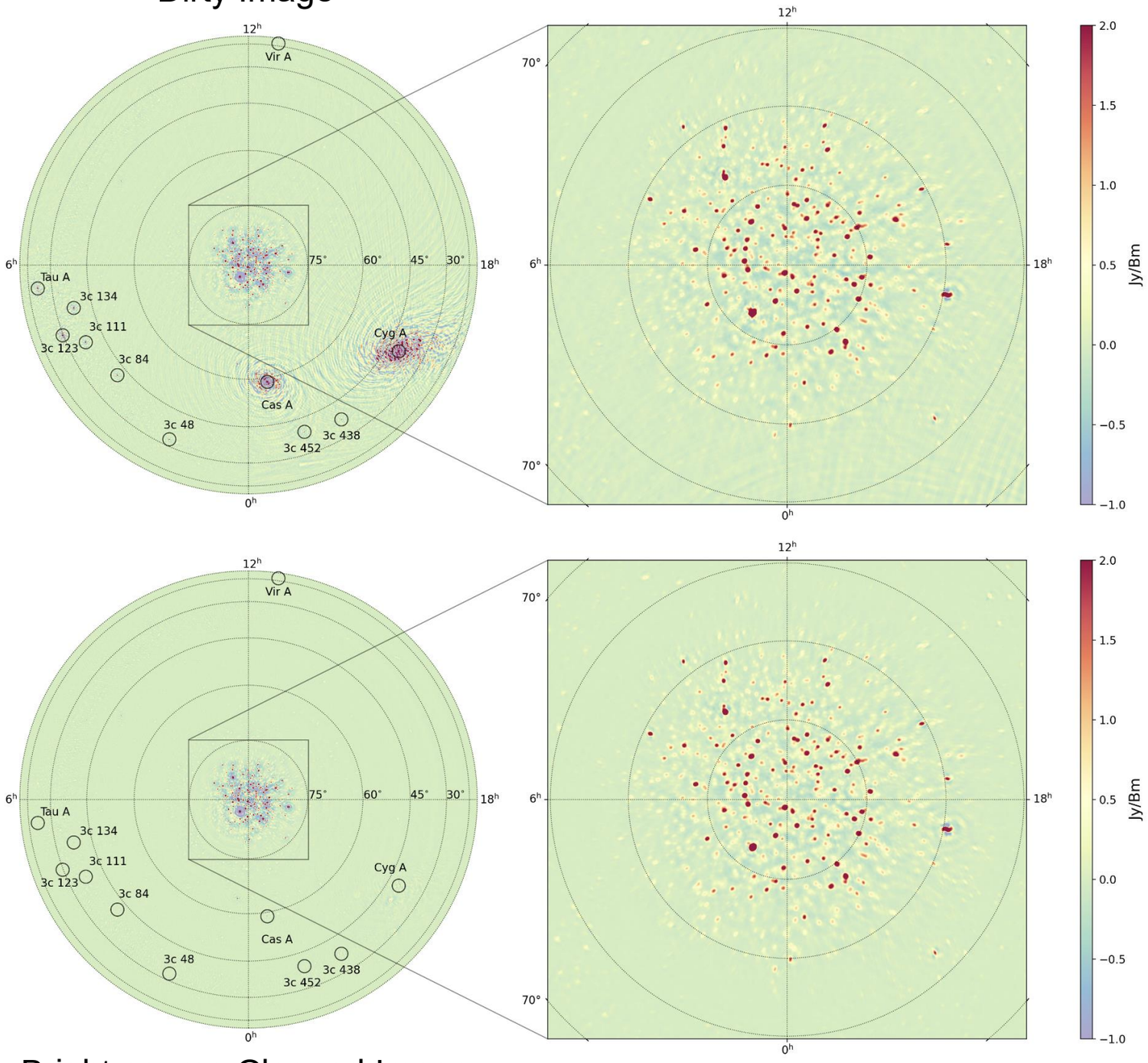
New Extension in Nançay Upgrading LOFAR: NenuFar

First data taken on NCP field in December 2018.
Cosmic Dawn Key Science Program started in 2020 and continuing.

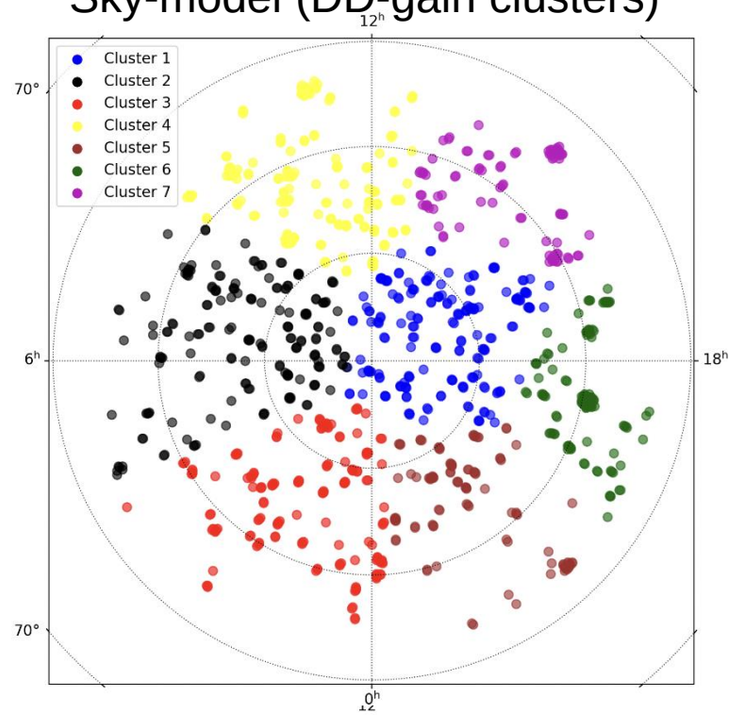
NenuFAR Cosmic Dawn Key Science Programme

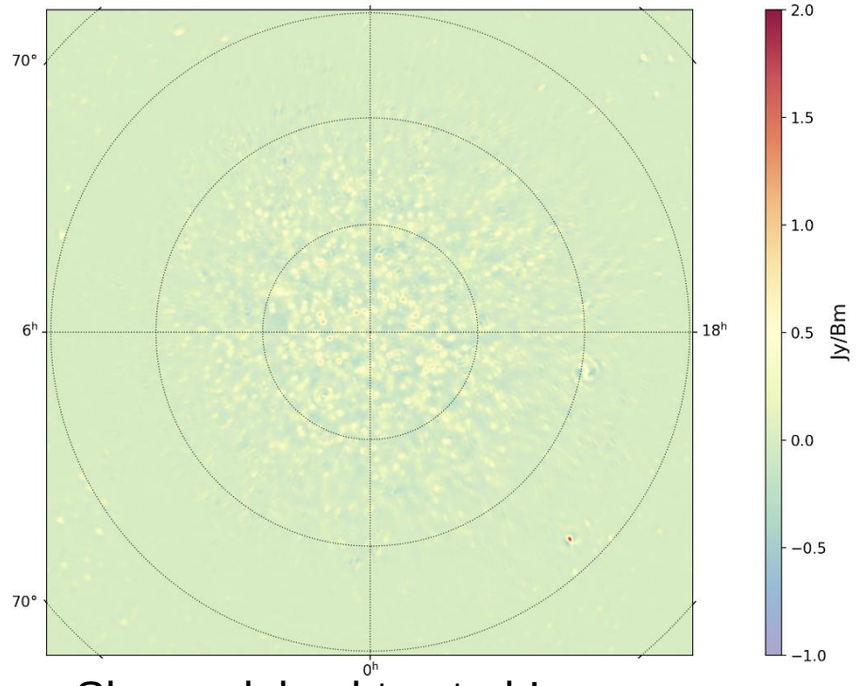
All sky model, calibration and imaging is essential: Cas A & Cyg A are the “enemies”!

Dirty Image



Sky-model (DD-gain clusters)





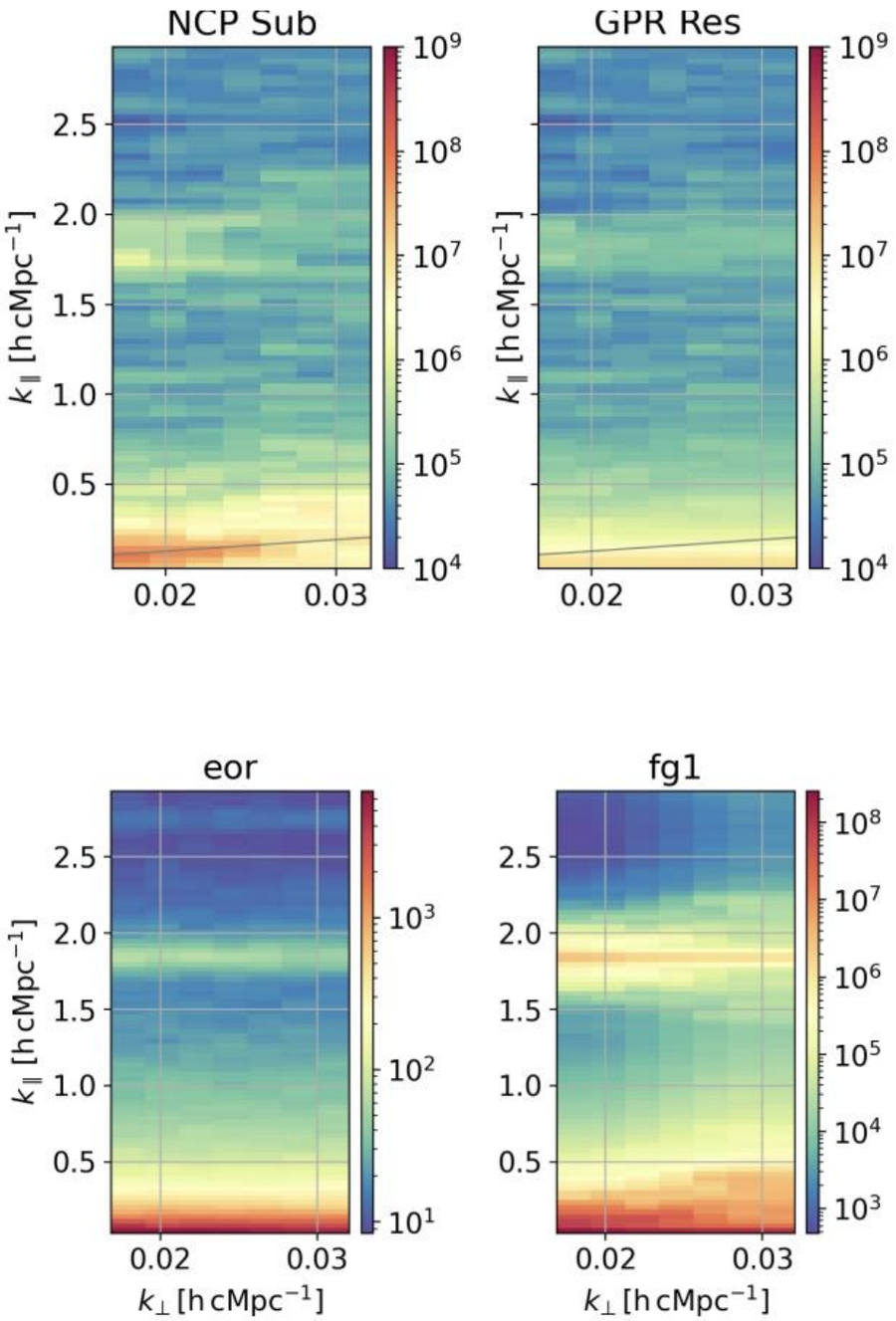
Bright-source Cleaned Image

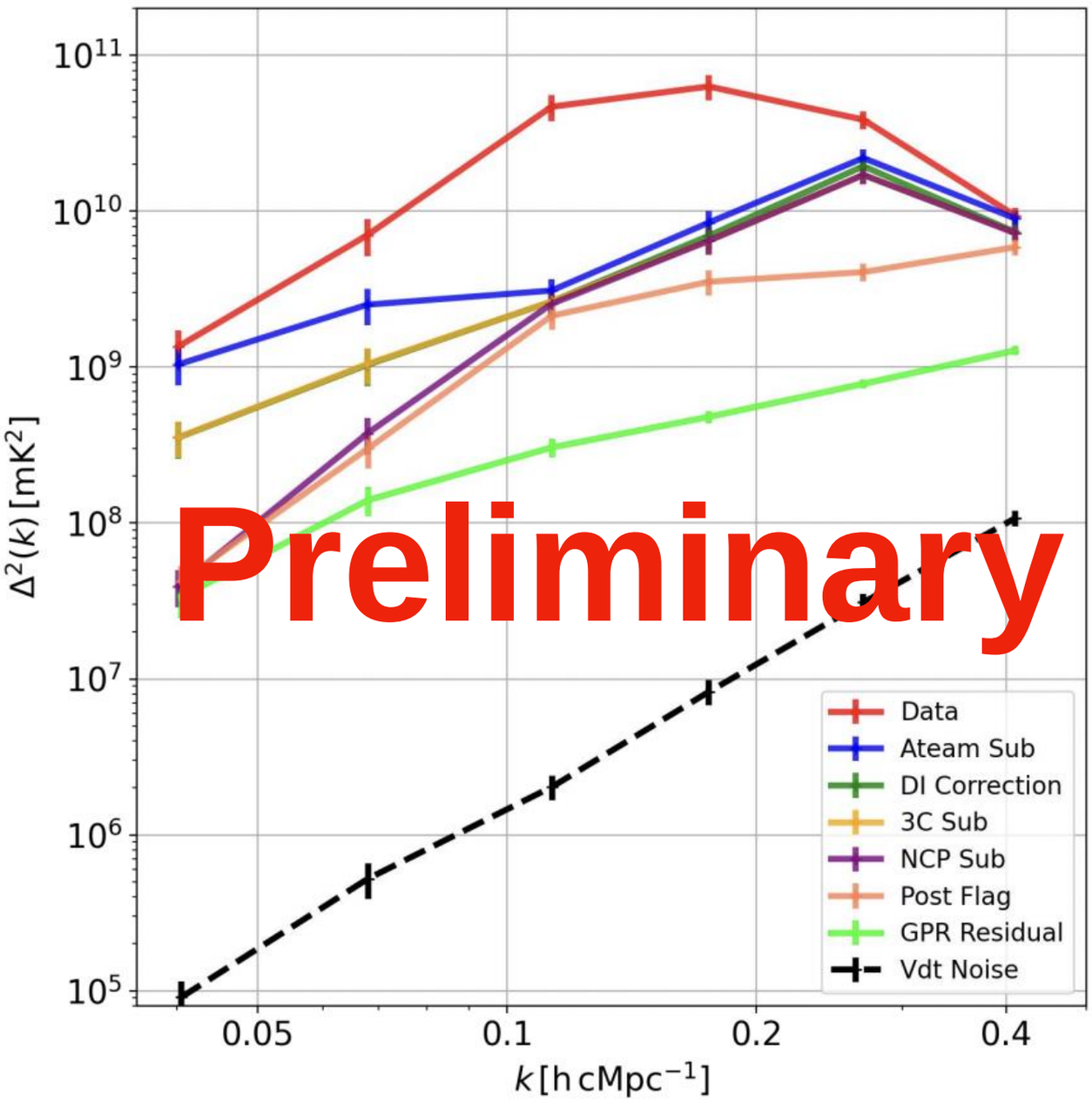
Sky-model-subtracted Image

Munshi et al. 2023, in prep

NenuFAR Cosmic Dawn Key Science Programme

Applying ML Gaussian Process Regression models, directly connected to 21-cm models (





Munshi et al. 2023, in prep

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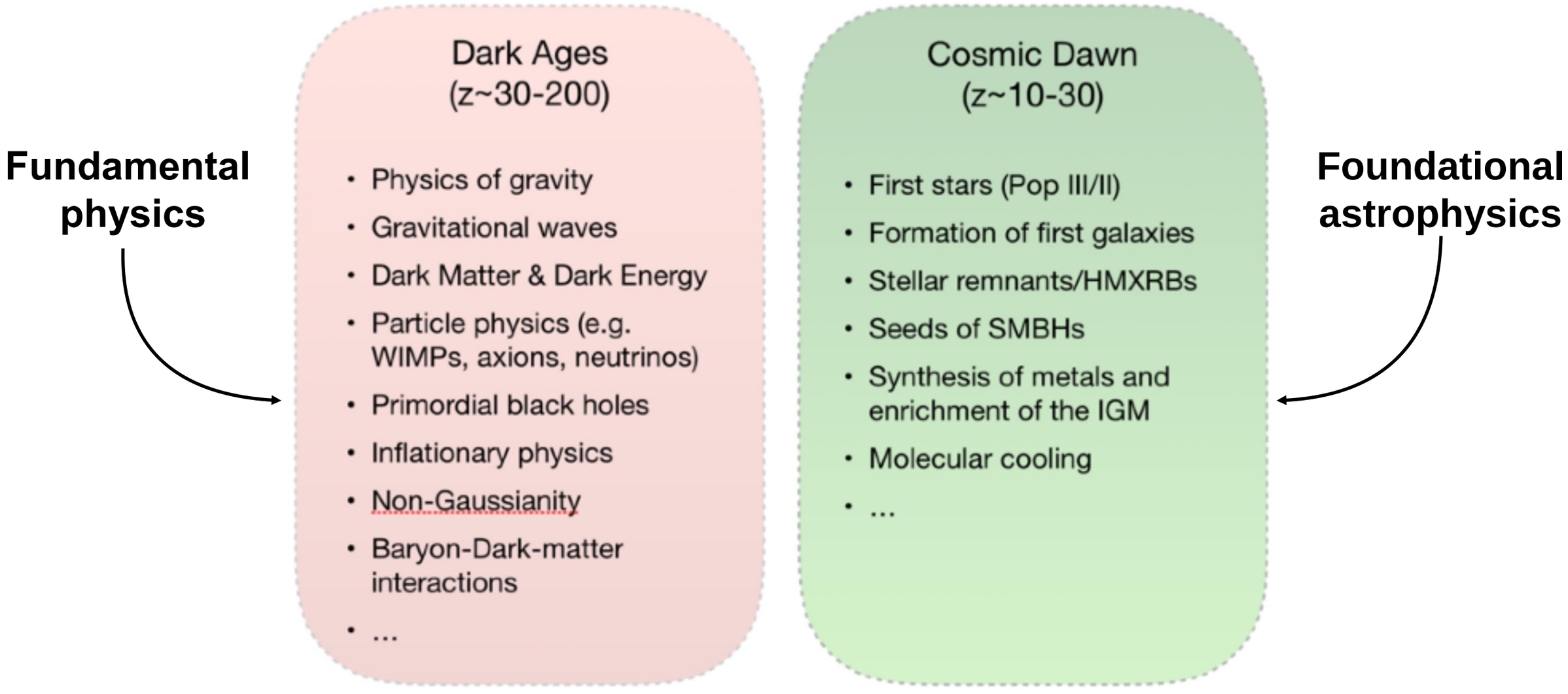
The Next Frontier: Dark Ages

21-cm Cosmology from the Moon & Space

LOFAR Family Meeting, Olsztyn, Poland, June 12-16, 2023

Dark Ages: Fundamental Physics

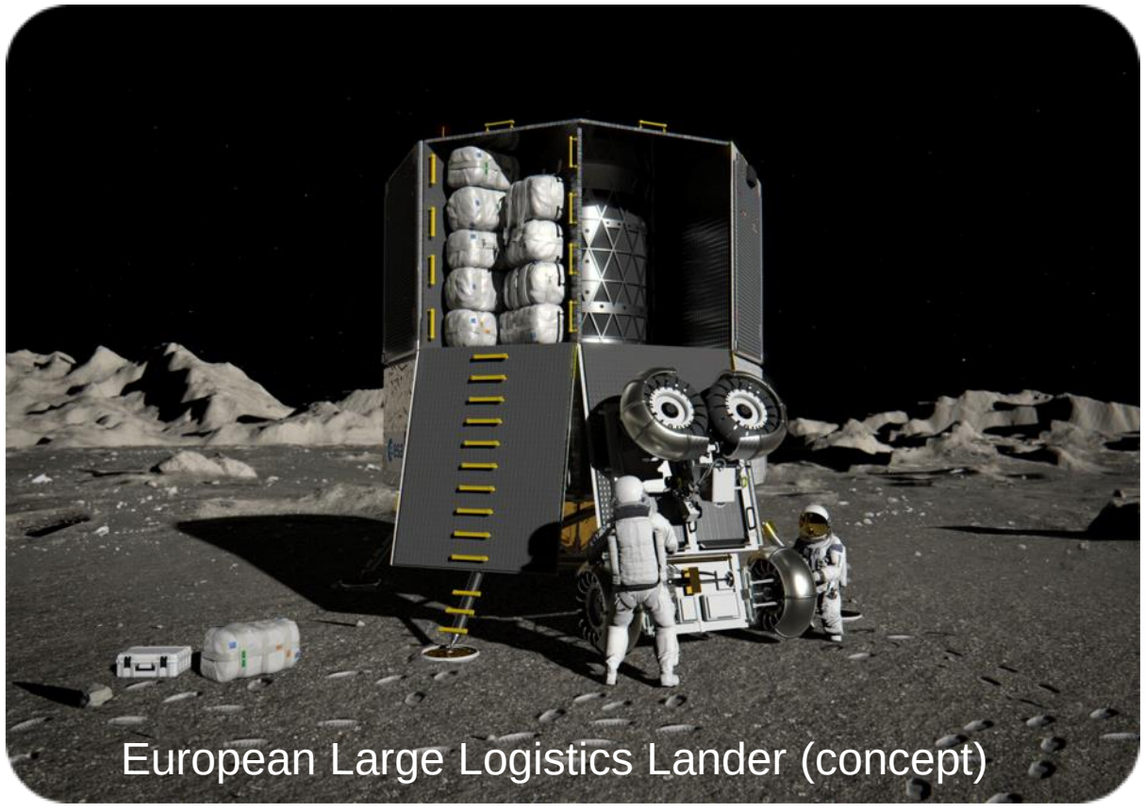
The standard model of physics plus the standard Cosmological model *exactly* predict the 21-cm signal of neutral during the Dark Ages: “simple" linear theory.
During the Cosmic Dawn (g)astrophysics is added.



Astrophysical Lunar Observatory (ALO)

ESA Explorer Mission Concept (Phase A study)

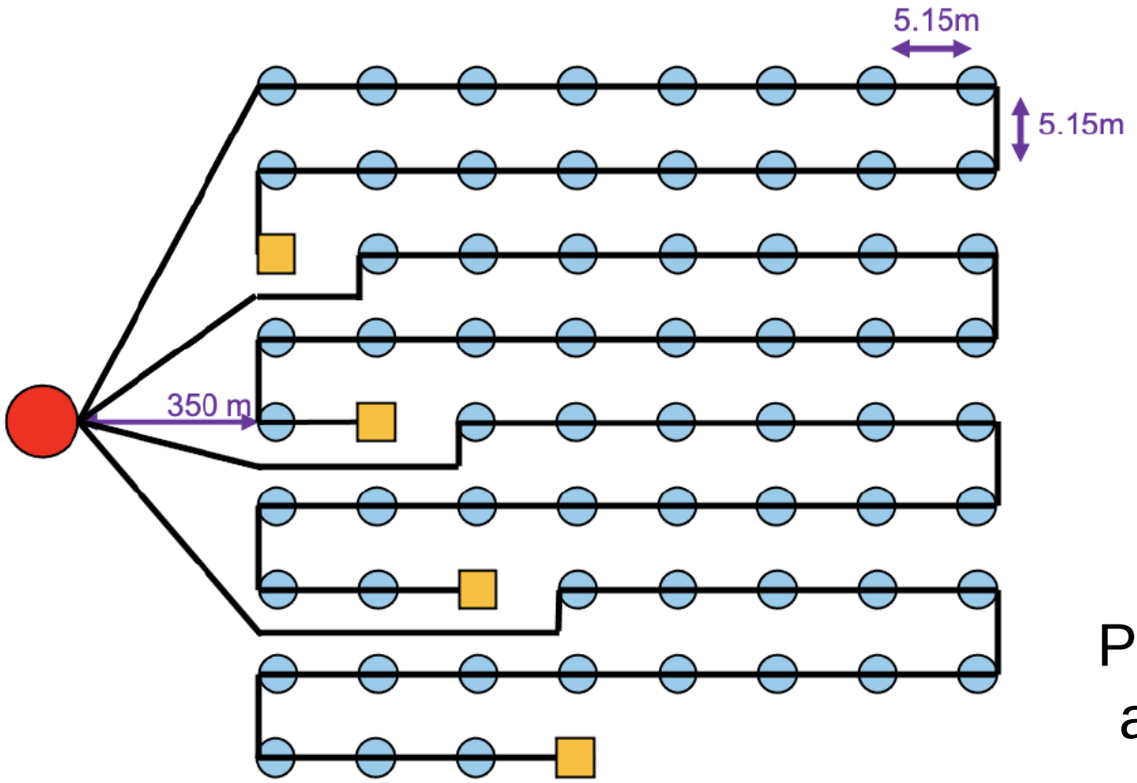
- Concept for a low-frequency radio telescope on the lunar surface (pole/far-side)
- Science payload on several of first EL3 landers
- Both global 21-cm signal receivers (pole/far-side) and array for 21-cm power-spectrum/tomography observations (lunar far-side)
- Covering Cosmic Dawn and Dark Ages redshifts (z>~15), needing >10^4 hours of integration.



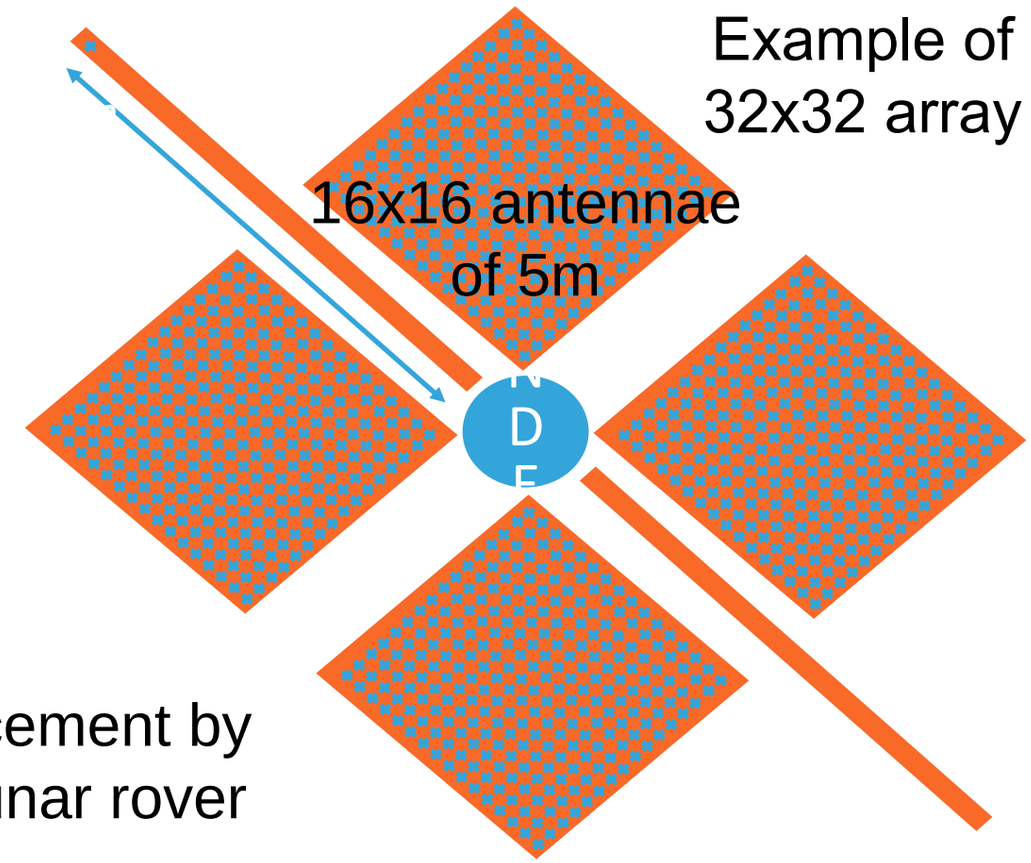
European Large Logistics Lander (concept)

Astrophysical Lunar Observatory (ALO)

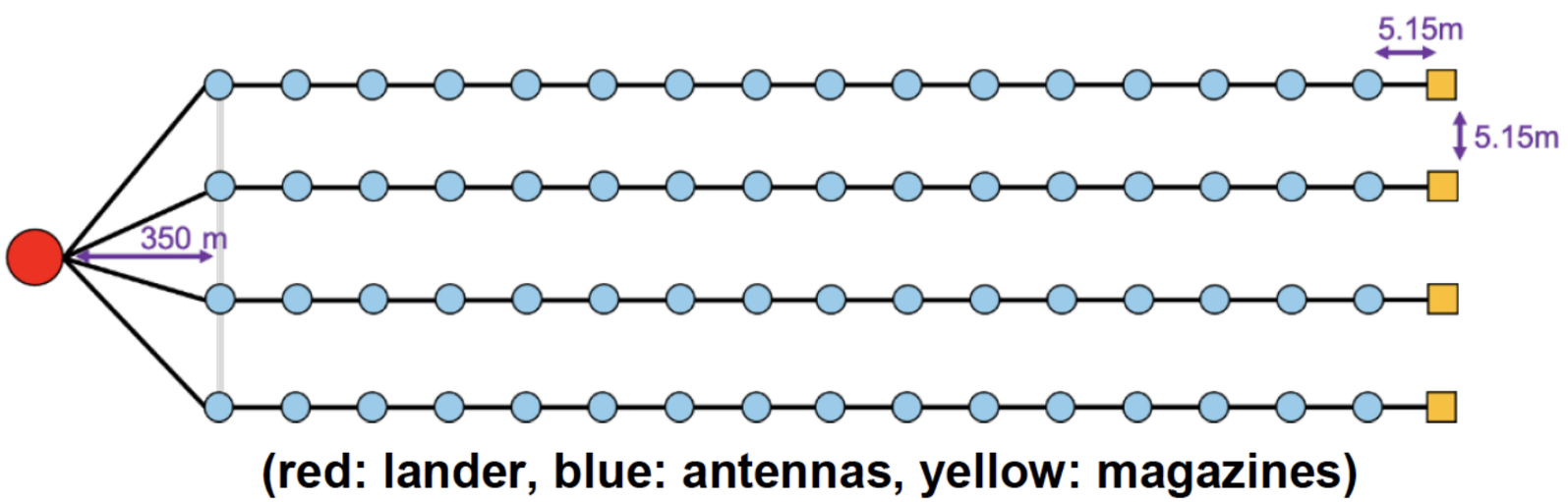
Basic concept of NxN array (power-spectrum)
with 4 outriggers (global signal)



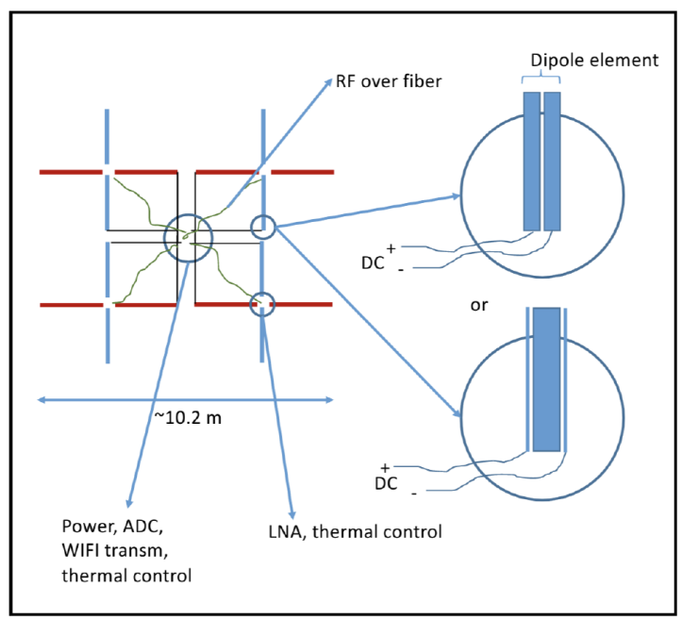
Example of
32x32 array



Placement by
a lunar rover

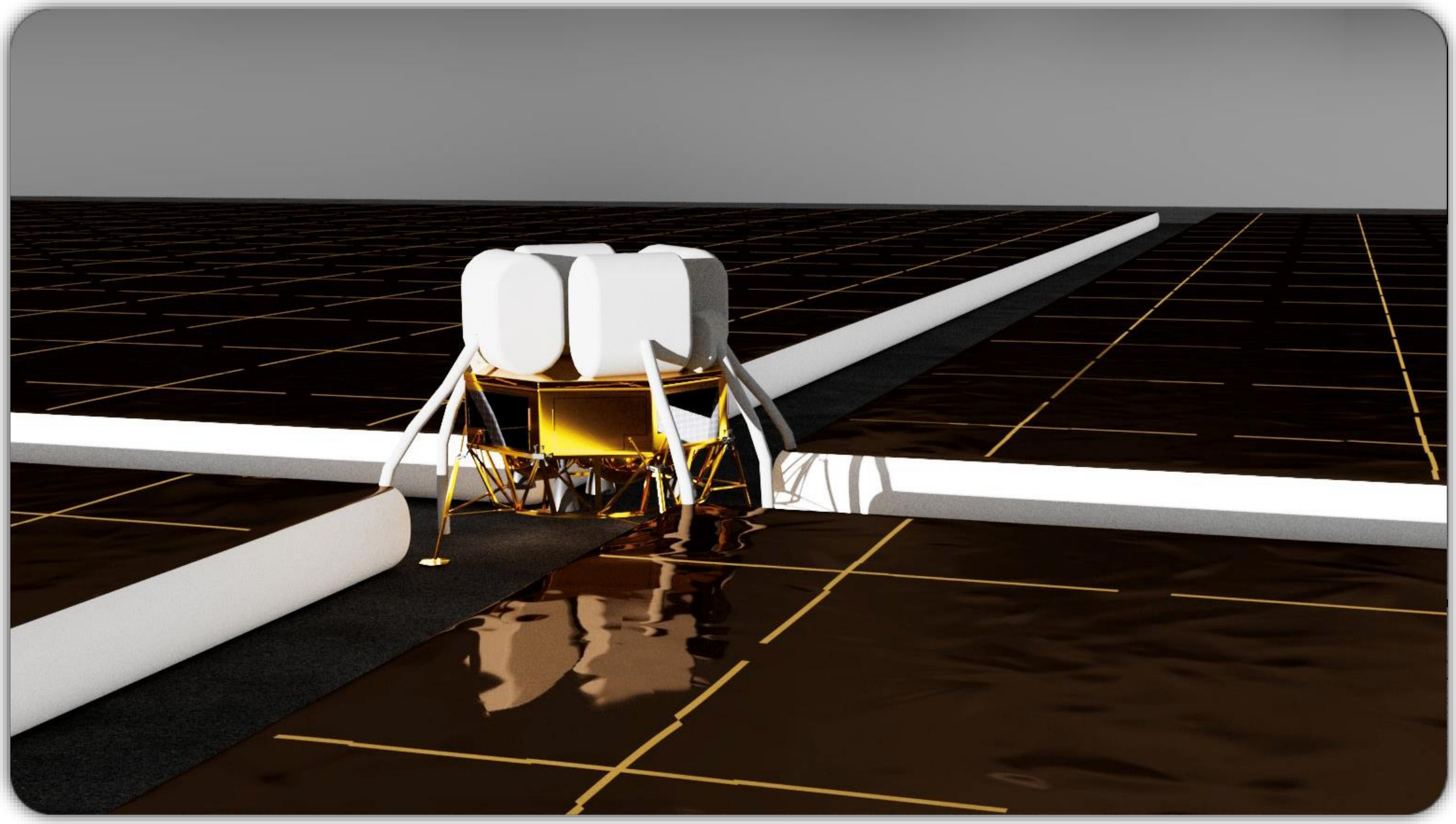


(red: lander, blue: antennas, yellow: magazines)



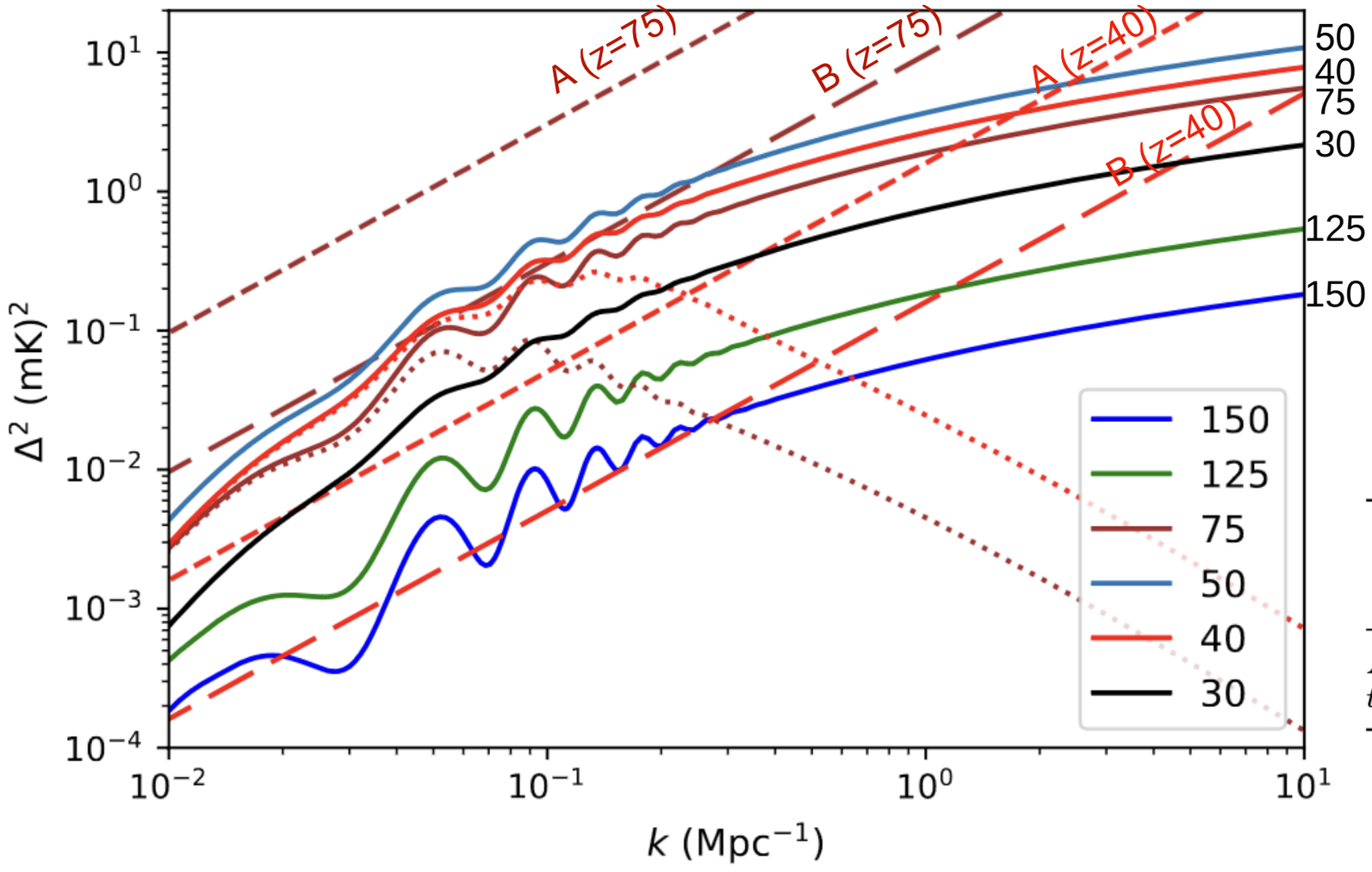
Astrophysical Lunar Observatory (ALO)

A conformal grid-like array (allowing for a spatial FFT correlation), shielded from (other) activities on the lunar surface, with up to four outrigger global 21-cm receivers placed at a distance.



Astrophysical Lunar Observatory (ALO)

Power-spectrum sensitivity for 16 (4x4), 1024 (32x32), 16384 (128x128) receivers:
Compact (f=1) array, 5m dipoles, BW=10MHz, 10^4h integration, half-sky



Mondal & Barkana 2023

	Configuration			
	D	C	B	A
$A_{\rm coll}$ [km^2]	100	100	10	10
$t_{\rm int}$ [hrs]	10,000	1,000	10,000	1,000

[Note an array of 128x128 5x5m dipoles has “only” $A_{\rm eff}$=0.4km^2 at 30MHz;
Larger $A_{\rm eff}$ than the SKA-low core and 100x SKA-low’s FoV at 50MHz]

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Summary & Conclusions

No detection yet, but we gained orders of magnitude in depth sometimes using the same data: no-one said this was easy!